

ECONOMY IN THE ERA OF DIGITAL TRANSFORMATION: TRENDS, OPPORTUNITIES AND PERSPECTIVES

Collective monograph

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ABSTRACT

The monograph "Economy in the era of digital transformation: trends, opportunities and perspectives" represents an interdisciplinary comprehensive study of the current state and key changes occurring in the socio-economic system under the influence of digital technologies. The work analyzes modern digitalization trends and the advanced experience of foreign businesses – from digital taxation and smart economy to the implementation of blockchain systems, digital governance platforms, and digital tools for remediation and revitalization. Particular attention is given to post-crisis recovery opportunities based on digital models, including sustainable development, investment attractiveness, and regional adaptability. The authors substantiate and propose the implementation of progressive approaches to digital policy, institutional governance, and the formation of competitiveness in the conditions of global transformation. This collective monograph encompasses theoretical analysis with applied solutions and is intended for scholars, practitioners, public administrators, and digital architects of the economy of the future.

Reforming the Personal Income Tax in Ukraine for the Post-War Perspective in the Era of Digital Transformation

This chapter of the monograph is devoted to a comprehensive analysis of the functioning of the personal income taxation (PIT) system in Ukraine for the period from 2018 to 2024. The focus is on the organizational conditions of tax collection, the impact of crisis factors (including the post-COVID-19 pandemic period and the period of full-scale war since February 2022), as well as the prospects for reform within the framework of large-scale digitalization and with consideration of behavioral economics. The authors substantiate the need to shift from a proportional to a progressive taxation scale, introducing behavioral and digital vectors as key directions of the studied transformation of the national economy. The study proposes specific measures: from the introduction of an active tax-free minimum to the use of Big Data, electronic declarations, and the functionality of the Diia application for the purpose of increasing transparency and administrative efficiency. The chapter forms the conceptual basis of a new tax philosophy, which is primarily focused on social justice, digital governance, and the sustainable recovery of the country.

Digital Drivers of Business Model Transformation in the Circular Economy Paradigm

This chapter of the monograph is devoted to an in-depth comparative analysis of EU countries in the context of a quantitative assessment of the impact of digitalization on the transformation of business models in the conditions of the transition to

a circular economy. In the study, the author developed and proposed for implementation a comprehensive scheme for assessing the level of digital–circular integration. The Integrated Digital Circular Economy Index (IDCEI) was substantiated and proposed for application; it includes key indicators of digital intensity and resource efficiency. Based on cluster analysis and scenario modeling, three development trajectories were identified: intensive digital integration, fragmented implementation, and digital stagnation. The main drivers of a successful transition were defined as the level of ERP system implementation, the Circular Material Use (CMU) rate, investments in circular transformation, and eco-efficiency performance. The practical significance of the developments proposed by the author may serve as a foundation for the development of digital–environmental policies, cross-country benchmarking, and integration monitoring, taking into account the need for institutional readiness and the strategic reorientation of business toward sustainable digital models.

Digitalization of Crisis Management Remediation: Assessment of Implementation and Development Prospects

This chapter of the collective monograph presents an in-depth analysis of the digitalization of remediation management in the context of crisis management, with a focus on the post-war recovery of Ukraine. The author reveals the evolution of the concept of remediation as a multifunctional process that combines environmental cleanup with the socio-economic revitalization of territories. The author's methodology for assessing the effectiveness of digital remediation management is presented, using multi-criteria models and Monte Carlo simulation. Particular attention is given to the integrated use of digital technologies – such as IoT, AI, unmanned aerial vehicles (UAVs), digital twins, GIS, and blockchain – for achieving a sustainable recovery effect. The proposed model, which includes a digitalization coefficient and an adaptive mechanism for parameter adjustment, will enable informed managerial decisions under conditions of uncertainty and limited resources, making it particularly relevant for Ukraine and other post-crisis countries that have faced emergencies of climatic, technogenic, and military nature.

Implementation of Blockchain Technologies and Smart Contracts as a Driver of International Investment Activity in the Post-War Recovery of Ukraine

This chapter of the monograph is dedicated to a comprehensive analysis of the potential for implementing blockchain technologies and smart contracts as a key driver of international investment activity in the process of post-war recovery of Ukraine. The authors argue that it is precisely transparency, trust, and automation provided by blockchain that are capable of eliminating the key barriers to attracting foreign investments. First and foremost, this concerns corruption risks and the non-transparent use of resources. The study presents a project model of a digital

platform that includes a public project registry, smart contracts for monitoring the execution of works, asset tokenization, and citizen participation in the post-war recovery process. The simulation modeling conducted confirmed that the use of blockchain solutions can significantly reduce investment risks and increase the resilience of capital inflows. Thus, the proposed approach can become the technological foundation of Ukraine's new investment image – transparent, digital, and focused on the effective recovery of the country.

Innovative Technologies and Digital Models in the Post-War Recovery of the Transport and Logistics System of Ukraine

This chapter of the collective monograph is devoted to an in-depth analysis of the role of advanced digital solutions in the recovery and modernization of Ukraine's transport and logistics system after the end of the war. The authors emphasize that the destruction requires not just restoration, but a digital reboot of the entire sector, which is strategically significant in the context of the revival of the national socio-economic system. It concerns the optimal implementation of IoT, Big Data, unmanned technologies, and blockchain. The authors present a simulation model of digital transformation based on the S-curve and Porter's model, which makes it possible to forecast the introduction of technologies in the long term. Based on a comparative analysis with leading countries of the world, practical recommendations are proposed for the digitalization of Ukraine's borders, multimodal logistics, and total IoT monitoring. The authors emphasize the necessity of a systemic approach and coordination between the state, business, and international partners to form a sustainable, integrated, and competitive logistics infrastructure of Ukraine in the nearest future.

Digital Transformation as a Factor in the Development of International Business in the Era of Digital Globalization

This chapter presents a comprehensive analysis of digital transformation as a key factor in the development of international business in the context of digital globalization. The study emphasizes that digitalization has ceased to be merely a technological trend and has turned into a strategically important tool for enhancing competitiveness in global markets. Particular attention is paid to assessing the impact of technologies such as artificial intelligence, Big Data applications, cloud solutions, IoT, and blockchain on the transformation of business models and operational processes. The study provides a detailed comparative measurement of the level of digital maturity in Central and Eastern European countries, as well as proposes an original index for assessing readiness for international digital expansion. The conclusion substantiates that companies with a higher level of digitalization have a greater chance of success in the international environment, which makes digital transformation

an integral part of sustainable development strategies and effective integration into the global economy.

Smart Economy in the Conditions of Post-War Recovery of Ukraine: Digital Tools of Remediation and their Impact on Regional Development

This chapter is devoted to an in-depth study of the concept of smart economy in the context of post-war remediation and revitalization of Ukraine, with an emphasis on the use of digital tools through the lens of regional development. The authors substantiate the importance of digital transformation as a cornerstone of effective recovery and propose an architecturally hybrid, context-sensitive model of smart economy, taking into account the behavioral perception of the population, institutional support, and regional specificities. The hybrid model and regional stratification proposed by the authors have practical significance and can be used by public authorities to develop regionally oriented strategies of digital transformation. It will make it possible to forecast and assess the effectiveness of digital solutions in the context of post-war recovery, as well as to determine the priority of regional investments and digital interventions.

Keywords

Digital transformation, smart economy, sustainability, post-war recovery, personal income tax, behavioral function, digitalization function, Consolidated Budget of Ukraine, State Budget of Ukraine, Local Budgets of Ukraine, Personal Income Tax Efficiency, Fiscal Efficiency of Personal Income Tax, elasticity of personal income tax, proportional tax, progressive tax, non-taxable minimum, social justice of taxation, tax culture, tax behavior, tax mentality, circular economy, business models, ERP systems, digital integration, cluster analysis, composite index, sustainable development, remediation, revitalization, digitalization, crisis management, Internet of Things (IoT), artificial intelligence (AI), digital twins, geographic information systems (GIS), unmanned aerial vehicles (UAVs), multi-criteria decision analysis (MCDA), adaptive management, Monte Carlo simulation, resilience, blockchain, smart contracts, international investment, financing, management, congruent development, transport and logistics system, economic diagnostics, managerial decisions, forecasting, benchmarking, digital transformation indicator, international business, regional development, phenotypic adaptation, inclusivity of digitalization, regional stratification.

CIRCLE OF READERS AND SCOPE OF APPLICATION

This monograph is addressed to a wide range of readers: scholars in the fields of economics and public administration, specialists in crisis management, digital technologies, cybersecurity, sustainable development, and behavioral economics; representatives of fiscal authorities, international investors, IT experts, consultants in logistics and ESG, as well as representatives of governmental bodies responsible for the post-war recovery of Ukraine and its positioning on the international stage.

The scope of application can be presented through the prism of its chapters, namely:

The chapter **"Reforming the Personal Income Tax in Ukraine for the Post-War Perspective in the Era of Digital Transformation"** will be primarily useful for managers of the financial system, including tax authorities, fiscal policy analysts, government structures, and parliamentarians. This chapter is applicable in the development of a fair taxation system, the digitalization of tax administration, and the implementation of behavioral economics elements into fiscal reforms.

The chapter **"Digital Drivers of Business Model Transformation in the Circular Economy Paradigm"** will be of interest to public administrators involved in the development and implementation of laws and policies aimed at supporting recycling and the rational use of resources, managers of economic entities integrating circular practices into production and consumption, environmental consultants, business model analysts, and specialists in sustainable development and digital transformation. The research findings can be practically applied by companies adopting circular economy principles, as well as by governments and international organizations developing digital-environmental policy.

The chapter **"Digitalization of Crisis Management Remediation: Assessment of Implementation and Development Prospects"** is primarily intended for specialists from various fields interested in crisis management of different types and scales, digital planning, and territorial recovery. The methodologies and models are useful for developers of remediation strategies, emergency management teams, and international partners engaged in the restoration of affected territories.

The chapter **"Implementation of Blockchain Technologies and Smart Contracts as a Driver of International Investment Activity in the Post-War Recovery of Ukraine"** will attract the attention of public officials developing and implementing legislation and policy aimed at the development of foreign economic activity, stimulation of investment flows, and improvement of Ukraine's investment climate. The research findings will be of interest to foreign investors, venture funds, and

representatives of the Ministry of Economy and the Recovery Agency. The conclusions and proposals can be applied in the design of transparent investment mechanisms, digital monitoring platforms, smart contracts, and asset tokenization.

The chapter **"Innovative Technologies and Digital Models in the Post-War Recovery of the Transport and Logistics System of Ukraine"** will be useful for logistics companies, transport agencies, the Ministry of Infrastructure, and international logistics platforms. The range of interested parties includes managers of all levels of the hierarchy who are directly or indirectly related to the topic of efficient infrastructure development. The conclusions and recommendations of the study can be applied to the digitalization of logistics infrastructure, the development of multimodal routes, and the implementation of IoT systems and unmanned solutions in the transport sector.

The chapter **"Digital Transformation as a Factor in the Development of International Business in the Era of Digital Globalization"** will be relevant and valuable for managerial staff of export-oriented companies, international trade organizations, and digital integration agencies. The research results can be used in the development of strategies for scaling digital advancement, conducting in-depth diagnostics and rapid analysis of companies' digital maturity, and expanding into new global markets.

The chapter **"Smart Economy in the Conditions of Post-War Recovery of Ukraine: Digital Tools of Remediation and their Impact on Regional Development"** is primarily addressed to representatives of top-level government authorities, such as the Ministry for Communities and Territories Development, regional administrations, digital development agencies, analytical centers, and urban planners. The study results can be used to design regionally adapted strategies for digital transformation, assess the digital receptiveness of territories, and develop policies for priority investment in smart solutions.

Thus, it can be confidently stated that the monograph "Economy in the Context of Digital Transformation: Trends, Opportunities, Prospects" represents not only a source of scientific inspiration but also an applied analytical tool for the development of sustainable development strategies in conditions of instability. It combines modern theoretical approaches with practical solutions, which makes it valuable for representatives of various fields of academic knowledge.

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INTRODUCTION

From Current Challenges to Future Opportunities: A Collective Scientific Perspective on Digital Transformation in the Era of Post-Crisis Recovery

The idea for this collective monograph emerged as a result of an urgent scientific and practical demand for a comprehensive analysis of the processes of digital transformation of the economy under the conditions of past and ongoing crisis phenomena – from global pandemics to military conflicts and climate disasters. Researchers from various fields of knowledge joined efforts for an in-depth study of transformational processes in national economies, paying particular attention to digital drivers of development, tools of post-crisis recovery, tax and investment strategies, regional resilience, as well as institutional adaptability.

The unification of international research efforts is driven by the need to compare and correlate the experiences of different countries in overcoming crises through digital tools and innovative models, as well as by the search for unconventional solutions to existing problems. This allowed the authors to broaden the geography of scientific inquiry, integrate macroeconomic, sectoral, and regional approaches, and develop practical recommendations relevant both for countries with developing economies and for those with a high level of digitalization.

Without exaggeration, it can be stated that digital transformation, since the beginning of the second decade of the 21st century, has ceased to be merely a technological phenomenon and has turned into a strategic foundation for stable socio-economic development, competitiveness, resilience, institutional renewal, and investment attraction. The issue of digital transformation becomes especially acute in the context of:

- post-war recovery of territories (as in the case of Ukraine);
- intensified global competition;
- increasing scale of technogenic and climate-related emergencies;
- transformation of logistics and tax models;
- increasing importance of trust and transparency in international economic relations.

The modern economy requires not just modernization – but a revision of the very paradigm of development, taking into account flexibility, adaptability, and digital governance. This monograph responds to that challenge by presenting a set of analytical studies in key areas, namely: digital taxation, smart economy, digital drivers of business model transformation in the paradigm of the circular economy, blockchain

in territorial recovery, digitalization in transport and logistics, digital remediation tools and their impact on regional development, as well as the associated national competitiveness and investment attractiveness.

The aim of this monograph is to form a scientifically grounded, interdisciplinary, and practice-oriented approach to studying the digital transformation of the economy in the context of: global and regional challenges, post-crisis recovery (including post-war scenarios), development of new models of digital policy, taxation and state anti-crisis management, strengthening sustainable territorial development, and attracting investment through transparent digital mechanisms.

The target audience of the monograph is quite broad. This monographic research may be interesting and useful to a wide range of specialists, namely: economists and financial analysts working in the field of taxation, digital public governance, sustainable development; public administrators in foreign economic activity and representatives of international organizations; specialists in investment activities focused on the implementation of digital projects in high-risk countries; professionals in digital technologies, blockchain system developers, electronic governance platform and smart infrastructure developers; academic researchers, postgraduate students, and students in economic and management fields.

According to the authors, this monograph reflects not only the current state of digital transformation processes in the economy but also sets a methodological and conceptual framework for further scientific and applied research, raising questions of strategic importance for planning the development of priority directions in the near future and for the swift achievement of the goals of a sustainable future.

CHAPTER 1

Reforming the personal income tax in Ukraine for the post-war perspective in the era of digital transformation

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Abstract

The research examines the functioning of the personal income tax system (PIT) in Ukraine over the period 2018–2024, with particular attention to the organizational conditions of its implementation, the outcomes of its operation during this timeframe, and proposals for its optimization in the post-war context, taking into account global trends in the digitalization of tax systems.

Within this framework, the authors outline the methodological foundations of the mechanism of personal income tax from the standpoint of its economic essence, the principles underlying its collection, and its core categorical characteristics – namely, political, financial, economic, and social. In view of the need to revise the philosophy of taxation in the post-war period, the study also considers the mechanism of personal income tax as a distinct behavioral and digital category.

The research further analyzes the implementation of personal income tax at various levels of the budget system. The findings suggest that this tax demonstrates relative resilience to changes in the economic environment. However, deep structural disruptions – such as the COVID-19 lockdowns and Russia's full-scale invasion of Ukraine – have the potential to adversely affect its performance.

The assessment of the effectiveness of the existing personal income tax collection mechanism indicates generally positive results. These include improvements in the gross tax gap, the tax collection rate, the level of fiscal significance of personal income tax in the state budget, the fiscal efficiency indicator, and the tax

efficiency ratio in relation to GDP. Positive dynamics are also observed in both the fiscal efficiency indicator and the elasticity coefficient.

Despite these favorable trends, the authors highlight the need to improve the mechanism of personal income tax in light of post-war recovery and evolving societal needs. It is demonstrated that the current proportional taxation system in Ukraine has several shortcomings, particularly its failure to account for social justice and income inequality. Accordingly, drawing on the theory of behavioral finance and international best practices, the authors propose transitioning to a progressive taxation model. This model would introduce differentiated tax rates based on income levels, thereby addressing behavioral aspects of taxation more effectively.

A key component of the study is the digitalization of personal income tax as a means of enhancing administrative efficiency. In this context, the principal directions of digital transformation include automatic income declaration, the use of Big Data analytics to identify tax risks, the implementation of electronic taxpayer services, and the expansion of functionalities within the Diia mobile application for individual taxpayers.

Keywords

Personal income tax, behavioral function, digitalization function, consolidated budget of Ukraine, state budget of Ukraine, local budgets of Ukraine, personal income tax efficiency, fiscal efficiency of personal income tax, elasticity of personal income tax, proportional tax, progressive tax, non-taxable minimum, social justice of taxation, tax culture, tax behavior, tax mentality.

1.1 Introduction

The personal income tax in Ukraine is an integral and active component of the national tax system, as well as a significant source of revenue for budgets at various levels. Although it is administered at the national level, revenues from the personal income tax constitute the primary source of local budget revenues. This, in turn, ensures the financial autonomy of regions and supports their financial and economic development.

The imposition of martial law in Ukraine led to large-scale population displacement, increased unemployment, and changes in the income structure of citizens. Consequently, the post-war reconstruction of Ukraine requires an effective tax policy that balances the budgetary needs of the state with the goal of stimulating economic activity among the population.

In this context, it is important to optimize the mechanism of personal income taxation, particularly its core elements – such as taxpayers, tax base, tax rates, tax

benefits, and exemptions – within the fiscal space, as well as in political and social dimensions. In the post-war perspective, the direction of reform should emphasize the establishment of preferential taxation for certain categories of taxpayers, the encouragement of labor migrant return, and the support of small and medium-sized enterprises through tax incentives. At the same time, reforms should consider current global trends in the development of tax systems, particularly the digitalization of tax administration processes.

The aim of this article is to identify effective ways to optimize the mechanism of personal income taxation in Ukraine in the context of post-war reconstruction and digital transformation, with a focus on adapting the core elements of taxation.

The key objectives of the study include clarifying the conditions under which the personal income tax mechanism was introduced and operated in Ukraine during the period preceding the full-scale invasion and under martial law, as well as developing proposals for its reform in the post-war context amid the active digitalization of tax processes.

The methodological framework of this article is based on the application of a range of general scientific and specialized methods. The dialectical method is used to explore and generalize the theoretical foundations and formulate the study's conclusions; the graphical-analytical method is employed to visualize intermediate and final results; horizontal and vertical analysis is applied to assess the performance of the personal income tax mechanism in terms of revenues to budgets at various levels; and modeling is used to summarize proposals for optimizing the tax mechanism.

It is worth noting that the issues discussed in this research have been extensively explored by many scholars and practitioners in the financial sector. However, under the conditions of martial law, the issue of improving the effectiveness of the personal income tax mechanism in the context of post-war recovery is gaining even greater relevance. Therefore, this research topic is positioned at the forefront of contemporary policy and academic discourse.

1.2 Conditions for the implementation of the personal income tax mechanism in Ukraine

Personal income tax plays a key role in the tax system of the state, as well as in its financial, economic and social spheres. Through the mechanism of implementation of this tax, the state regulates the level of redistribution of resources, affecting the indicators of social inequality and employment, the size of the shadow economy, the demographic situation and regional development.

The mechanism of functioning of the personal income tax is interpreted as "a set of tax methods and forms, instruments and levers of influence on tax relations arising from the withdrawal and use by the state of a part of the income of individuals (households)" [1]. However, it should be noted that this approach considers only administrative components, and it is necessary to focus on the elements of the personal income tax as the basis of its mechanism.

Other researchers emphasize that the mechanism of personal income tax functioning is "...one of the most important legal and fiscal instruments by which the state provides itself with the necessary resources to finance various types of social activities" [2]. This definition focuses primarily on the fiscal dimension of the tax mechanism, although it also has a significant impact on shaping an adequate level of social protection for citizens.

Proceeding from the position that there are three models of personal income taxation (global, decomposition and mixed), in particular in the context of the global model, personal income tax "...is one of the taxation instruments whose main purpose is to take into account the ability to pay contributions in order to ensure equality of social approaches among ... taxpayers". In this case, equality "...is widely used in the economic and tax sphere, is synonymous with justice and includes two orientations: horizontal and vertical" [3]. This perspective highlights another important aspect of the personal income tax mechanism – its role in achieving social justice in taxation.

However, the most comprehensive approach is the one according to which the PIT mechanism is implemented (and, accordingly, has an impact) at three levels: economic, where part of the income is alienated in favor of the state; political, where financial and tax policy is developed and implemented taking into account the interests of different segments of the population; social, where the tax stimulates the economically active population to work, increasing their own income and improving their well-being [4]. This vision of the mechanism of functioning of the personal income tax fully reflects its role in the life of the state.

As noted above, the basis of the personal income tax mechanism is its elements. According to V. Galushko, they should be divided into two groups: basic and additional. The author includes such elements as the taxpayer, the object of taxation and the tax rate in the category of basic elements; additional elements include tax exemption, tax base, tax quota, tax agent and regulation of the procedure for calculation and payment of tax [5]. In general, it is possible to agree with the author's opinion, but there are some additions: when looking for ways to optimize the functioning of the personal income tax, the main attention should be paid to such elements as the taxpayer, the object of taxation, the tax base, the tax rate and the tax exemption. In other words, they should be considered as the main ones.

Considering the outlined framework, it is worth paying attention to the functions performed by the personal income tax mechanism. They include, in particular, fiscal and distributional-regulating [6]; social-regulating [7]; economic, financial, political, social [4]; fiscal, stimulating, regulatory. It is possible to believe that the personal income tax mechanism should also include such functions as behavioral, which will take into account the peculiarities of psychological and social factors influencing the taxation process, and, given the active digitalization of economic processes, digitalization, which will be based on steps to increase the level of tax transparency and taxpayers' access to information.

It is equally important to outline the principles on which the personal income tax mechanism is based: universality of taxation; mandatory; fairness and equity of tax burden distribution [4]; fairness and responsibility; economic efficiency; convenience [8]; efficiency, neutrality, horizontal and vertical justice; economic efficiency [9]. All these principles characterize the personal income tax and its role in the country's economy – ensuring fairness of taxation through the distribution of financial resources (income).

The mechanism of personal income tax in Ukraine has developed over an extended historical period, including under conditions of long-term foreign domination. As a result, the national personal income tax mechanism is marked by a low level of tax culture and public awareness, elements of compulsion, excessive tax burdens, and a complex legal framework. These factors contribute to the instability of the tax system and complicate the search for effective ways to improve it under current market conditions – and more critically, under the circumstances of post-war reconstruction in Ukraine.

At the same time, personal income tax as a distinct category – considered through the lens of its spheres of influence – has acquired certain features, illustrated in **Fig. 1.1**.

The above characteristics of the mechanism of functioning of the personal income tax are considered mainly from the standpoint of three main categories: political, within which it acts as a tool for balancing the interests of the state and taxpayers; financial and economic, which understands it as a means of redistributing part of the funds (income) of taxpayers in favor of the state; social, since it is the personal income tax that can affect both the quality of life of the country's population and its financial behavior. Taking the social aspect as a foundation, it is possible to propose the behavioral category as one of the key ones for characterizing the personal income tax, since this type of taxation can be an active tool for shaping the tax mentality of the nation and the tax culture of taxpayers. And given the growing digitalization of economic processes, it is proposed to consider the personal income tax as an element of the overall digital economic space of the state.

Since Ukraine's independence, the personal income tax mechanism has evolved from a progressive scale to a proportional one. However, in the current environment

of military aggression and stagnation of the country's economy, it is necessary to review the conditions of its application.

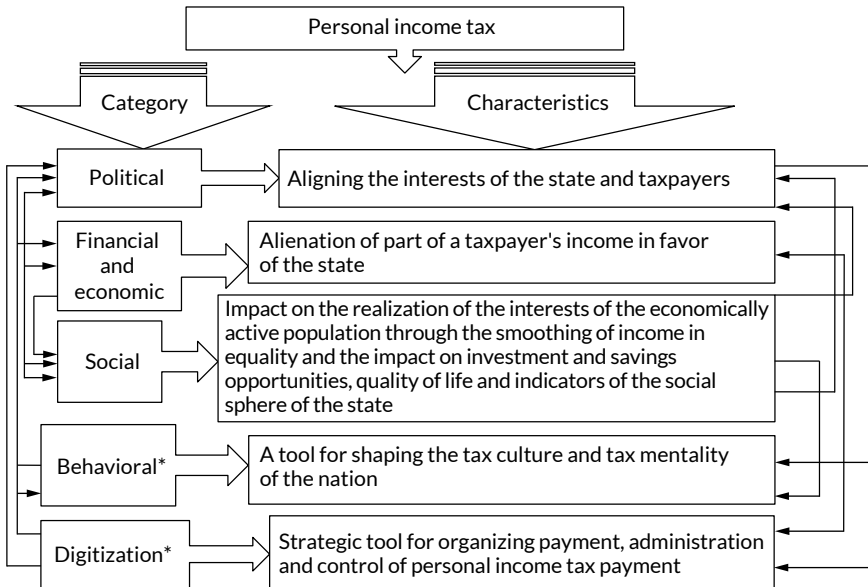


Fig. 1.1 Main characteristics of the personal income tax mechanism and their interrelation
Source: generalized from [2]
*Note: *author's proposal*

At present, the system of personal income taxation is marked by a number of systemic issues. It imposes a significant tax burden on individuals, which reduces both labor and entrepreneurial activity, results in insufficient budget revenues, contributes to the widening of the income gap, and stimulates the growth of the shadow economy. Consequently, the personal income tax system fails to positively influence the investment climate, the development of a skilled labor market, or the improvement of living standards and the social well-being of the population.

1.3 Peculiarities of the personal income taxation mechanism in Ukraine

The economy of each country has its own peculiarities that affect the efficiency of the tax system. Among other taxes, personal income tax is one of the most efficient

in terms of the number of taxpayers. However, it should be remembered that the main purpose of its functioning is to ensure the fulfillment of the fiscal function while creating equal tax pressure on taxpayers.

Currently, the personal income tax in Ukraine is a national tax, but its revenues are mainly generated by local budgets. In particular, in accordance with the rules established in 2022, 64% of the personal income tax paid in the territory of village, town and city territorial communities is credited to the budgets of village, town and city territorial communities; 15% – to regional budgets, 21% – to the state budget; the revenues of this tax in the territory of Kyiv are distributed as follows: 60% – to the state budget, 40% – to the budget of the city of Kyiv.

It is worth noting that personal income tax is levied at proportional (linear) rates, with the basic rate of 18% applied to income in the form of wages, other incentive and compensation payments and remuneration received in connection with employment, as well as passive income. The latter are taxed at slightly different rates: 5% is applied to taxation of inheritance transactions (0% for inheritance received from persons of the 1st and 2nd degree of kinship) and transactions on sale (exchange) of real estate (0% for the first sale of real estate during the year); 9% – for income in the form of dividends on shares, investment certificates or corporate rights accrued by foreign legal entities, joint investment institutions or business entities that are not income tax payers.

Once a year, resident taxpayers who receive income in the form of wages can take advantage of a tax rebate on personal income tax. To do so, they must submit a tax return on their property and income to the tax service. The declaration must indicate the fact of the purchase of goods or services specified by law (e.g., part of the interest on a mortgage loan, payment of tuition fees for the taxpayer or a person of the first degree of kinship, etc.), which is confirmed by copies of the relevant payment documents.

The tax social privilege is a declarative instrument to reduce the personal income tax burden for low-income taxpayers. However, the limit of its application – the subsistence minimum for an able-bodied person as of January 1 of the reporting tax year multiplied by 1.4 and rounded to the nearest 10 hryvnias – makes it virtually ineffective. And this contributes to the fiscalization of the personal income tax, although it should have a significant social content.

However, despite the existence of significant controversial and even problematic issues, the personal income tax in Ukraine is quite effective in terms of accumulating funds. At the same time, before the full-scale invasion, the personal income tax was one of the three main sources of revenue for the consolidated budget of Ukraine (**Fig. 1.2**).

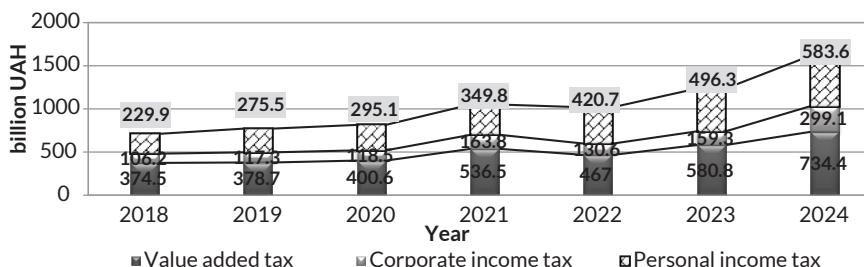


Fig. 1.2 Dynamics of the main taxes in the revenues of the consolidated budget of Ukraine in 2018–2024, %
Source: [10–15]

Personal income tax revenues in the consolidated budget revenues of Ukraine (**Fig. 1.2**) are characterized by a steady positive trend, with a total increase of 353.7 billion UAH in 2024 compared to 2018. At the same time, the increase in corporate income tax revenues amounted to 192.9 billion UAH, and value added tax – 359.9 billion UAH. In other words, the quantitative growth of personal income tax revenues in the reporting period was 6.2 billion UAH less than the growth of the value added tax accumulated in the budget.

However, these indicators provide a quantitative characterization of taxation, while the qualitative aspects are much more interesting, primarily the share of these taxes in the revenues of the consolidated budget of Ukraine and the change in their annual growth rates (**Table 1.1**).

In the pre-war period under review (2018–2021), the highest growth rates were recorded for value added tax revenues, while personal income tax demonstrated the greatest stability. Notably, the share of personal income tax in the revenues of the consolidated budget of Ukraine remained consistently stable during this period.

It is also important to highlight the adverse fiscal outcomes of 2020, which resulted from the COVID-19 pandemic and related global quarantine restrictions. In that year, the growth rates for key taxes were as follows: 5.5% for value added tax, 1.0% for corporate income tax, and 6.6% for personal income tax. However, by 2021, the fiscal situation had stabilized, with growth rates reaching 25.5% for value added tax, 27.7% for corporate income tax, and 15.6% for personal income tax, respectively.

During the period 2022–2024, which coincided with the onset of Russia's full-scale invasion of Ukraine and the imposition of martial law, personal income tax demonstrated notable fiscal resilience. Despite a decline in its share of consolidated budget revenues from 21.0% in 2021 to 19.2% in 2022, it was the only major tax to exhibit a positive annual growth rate of +16.9%. In contrast, value added

tax revenues decreased by 14.9%, and corporate income tax revenues fell by 25.4%. Although the share of personal income tax in total revenues during 2022–2024 did not return to pre-war levels, particularly those of 2021, its growth dynamics remained relatively stable throughout the entire 2018–2024 period – excluding the downturn in 2020. This resilience can largely be attributed to the relatively broad and well-defined tax base, as well as the large number of registered taxpayers.

Table 1.1 Dynamics of the share of major taxes in the revenues of the consolidated budget of Ukraine and their growth rates in 2018–2024, %

Year	Indicator	Value added tax	Corporate income tax	Personal income tax
2018	specific gravity	31.6	9.0	19.4
	growth rate	+16.2	+30.9	+19.2
2019	specific gravity	29.4	9.1	21.4
	growth rate	+1.1	+9.5	+16.6
2020	specific gravity	29.1	8.6	21.4
	growth rate	+5.5	+1.0	+6.6
2021	specific gravity	32.3	9.9	21.0
	growth rate	+25.5	+27.7	+15.6
2022	specific gravity	21.3	5.9	19.2
	growth rate	–14.9	–25.4	+16.9
2023	specific gravity	18.7	5.1	16.0
	growth rate	+19.6	+18.0	+15.2
2024	specific gravity	20.5	8.3	16.3
	growth rate	+20.9	+46.7	+15.0

Source: [10–15]

Overall, these findings suggest that personal income tax is relatively resistant to macroeconomic shocks. More broadly, tax revenue performance is closely linked to both the adaptability of the chosen taxation methodology and the overarching objectives of the state's fiscal policy (**Fig. 1.3**).

In conclusion, based on the analysis presented in **Fig. 1.3**, it can be stated that – despite existing shortcomings – the mechanism of personal income tax functioning demonstrates a notable capacity to adapt to both external and internal changes in the economic environment. This adaptability ensures the relative stability of the tax over time.

Although personal income tax is administered at the national level, it primarily serves as a source of revenue for local budgets, in accordance with the distribution

procedures outlined in the Budget Code of Ukraine. Accordingly, it consistently plays a key role in financing budgets at various levels of the budget system (**Table 1.2**).

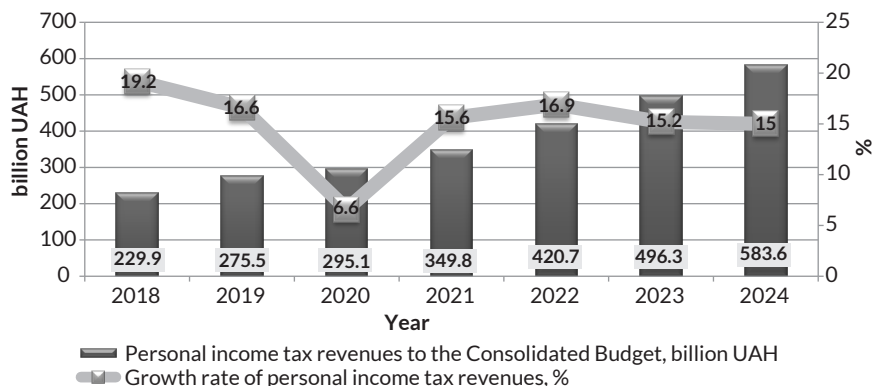


Fig. 1.3 Dynamics of indicators of the personal income tax presence in the consolidated budget of Ukraine in 2018–2024
Source: [10–15]

Table 1.2 Indicators of the functioning of the personal income tax in local budget revenues in 2018–2024

Indicator	2018	2019	2020	2021	2022	2023	2024	Deviation 2024 from 2018 (+,-)
Local budget revenues, billion UAH	562,4	560,5	471,5	580,7	555,1	652,6	679,5	+117,1
Tax revenues of local budgets, billion UAH	232,5	270,5	285,6	346,7	393,5	434,5	441,4	+208,9
Personal income tax, billion UAH	147,5	175,7	187,6	228,3	285,8	304,9	285,4	+137,9
Share of personal income tax in local budget revenues, %	26.2	31.3	39.8	39.3	51.5	46.7	42.0	+15.8
Share of personal income tax in local budget tax revenues, %	63.4	65.0	65.7	65.8	72.6	70.2	64.7	+1.3

Source: [10–16]

During the period under review (**Table 1.2**), personal income tax remained a key source of local budget revenues. Over this time, its share in the total volume of local

budget revenues increased by 15.8 percentage points, reaching 42.0% by the end of 2024. On average, from 2018 to 2024, personal income tax accounted for 66.8% of local tax revenues, reflecting an overall increase of 1.3 pp.

The consistently high share of this tax in local budget revenues can be attributed, in particular, to the administrative-territorial reform implemented under the 2022 legislative framework. According to the current distribution mechanism, 64% of personal income tax paid within the territories of village, town, and city territorial communities is allocated to their respective local budgets; 15% is directed to regional budgets, and 21% – to the state budget. In the case of Kyiv, the distribution differs: 60% is transferred to the state budget, while 40% remains in the city budget.

In this context, it is important to find out the parameters of the fiscal efficiency of the personal income tax mechanism, in particular, its impact on the state economy. To accomplish this task, it is possible to calculate the following indicators:

- gross tax gap;
- tax collection rate;
- the level of fiscal significance of the tax in the state budget;
- fiscal efficiency indicator, as a percentage;
- tax efficiency as a percentage of GDP.

The calculation of the gross tax gap, which is calculated as the difference between the actual accumulated and planned amount of tax payments, allows to assess the actual reliability of their planning. From this point of view, the tax collection rate is also analyzed, which is calculated as the ratio of the actual tax amount collected to the planned revenue figure (Table 1.3).

Table 1.3 Dynamics of certain indicators of fiscal efficiency of the personal income tax in 2018–2024

	Planned personal income tax revenues, billion UAH	Actual personal income tax revenues, billion UAH	Gross tax gap, billion UAH	Personal income tax collection rate, %
2018	227,7	229,9	+2,2	101.0
2019	244,3	275,5	+31,2	112.8
2020	276,7	295,1	+18,4	106.6
2021	343,6	349,8	+6,2	101.8
2022	408,9	420,7	+11,8	102.9
2023	588,3	496,3	–9,2	84.4
2024	575,8	583,6	+7,8	101.4

Source: [17–22]

According to our calculations (**Table 1.3**), actual personal income tax revenues consistently exceeded planned figures throughout 2018–2024. The most significant positive deviation – 31,2 billion UAH – was recorded in 2019. The only exception was 2023, when the gross tax gap reached a negative 9,2 billion UAH. These results suggest a generally high degree of accuracy and reliability in the tax planning process for personal income tax.

Particular attention should be paid to the calculated tax collection level (**Table 1.3**). Overall, the actual receipts of personal income tax to the consolidated budget of Ukraine during the analyzed period showed only minor deviations from forecasted amounts. In 2019, revenues exceeded the planned level by 12.8%, whereas in 2023, they fell short by 15.6 pp.

This decline can be explained by the aftermath of Russia's full-scale invasion and the temporary occupation of Ukrainian territories, which led to the suspension of many enterprises and private entrepreneurs – entities that previously ensured employment and generated income subject to personal income tax. The situation was further aggravated by the fact that most individual taxpayers in Ukraine rely on a single source of income – wages.

Nevertheless, the situation has gradually begun to stabilize, largely due to an increase in the number of taxpayers with a higher tax base, particularly military personnel. This trend highlights that, while personal income tax revenues remain relatively stable amid adverse macroeconomic conditions, they are nonetheless sensitive to profound structural and infrastructural shifts. At the same time, the effectiveness of the current tax planning mechanism has been largely confirmed under these conditions.

The next indicator to assess the effectiveness of the PIT collection mechanism is its fiscal value in the budget, which is calculated as a percentage of the amount of tax received by the respective budget level to the amount of revenues of the respective budget. Let's consider this indicator at the level of consolidated, state and local budgets of Ukraine, since the personal income tax is present in their revenue side (**Table 1.4, Fig. 1.5**).

Throughout 2018–2024, there was a positive trend in both the overall revenue performance of the budget system and the specific indicators of personal income tax revenues (**Table 1.4**). At the level of local budgets, revenues from this tax increased by 119,3 billion UAH, or 186.3%, in 2024 compared to 2018. At the state budget level, the increase amounted to 234,4 billion UAH, or 355.6%.

This significant growth in state budget revenues is primarily attributed to the revision of the distribution rules for personal income tax among the different tiers of the budget system.

Based on the indicators presented in **Table 1.4**, let's calculate the indicator of the fiscal importance of the tax in the revenues of these budgets (**Fig. 1.4**).

Table 1.4 Dynamics of personal income tax revenues and budget revenues of different levels of Ukraine in 2018–2024, billion UAH

Indicator	2018	2019	2020	2021	2022	2023	2024	Deviation 2024 from 2018 (+,-)
Consolidated budget revenues	1184,3	1289,8	1376,7	1662,3	2196,3	3104,3	3587,8	+2403,5
State budget revenues	928,1	998,3	1076,0	1296,9	1787,4	2672,0	3122,7	+2194,6
Local budget revenues	562,4	560,5	471,5	580,7	555,1	652,6	679,5	+117,1
Personal income tax revenues to								
Consolidated budget of Ukraine	229,9	275,5	295,1	349,8	420,7	496,3	583,6	+353,7
State budget of Ukraine	91,7	69,3	117,3	137,6	148,4	350,8	326,1	+234,4
Local budgets of Ukraine	138,2	165,5	177,8	212,2	171,4	289,4	257,5	+119,3

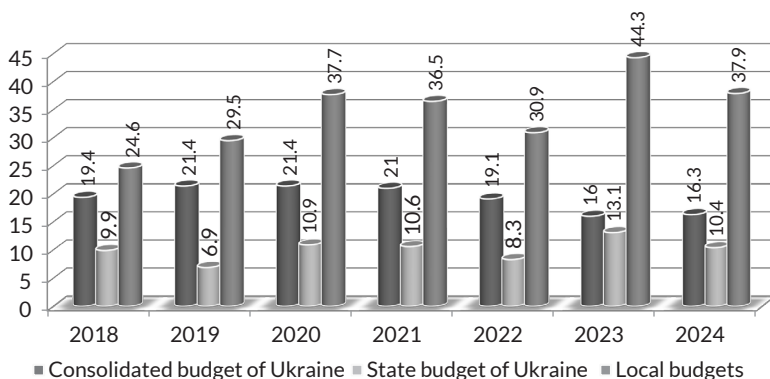


Fig. 1.4 Dynamics of indicators of fiscal significance of the personal income tax at the levels of the budget system of Ukraine in 2018–2024, %

In 2018–2024, the following trend in the level of fiscal significance of the personal income tax was observed (**Fig. 1.4**): at the level of the consolidated budget of Ukraine, from 2018 to 2020, there was a positive upward trend in the

indicator (+2.0 pp), and starting in 2021, downward trends dominated (the deviation of 2024 from 2021 was -4.7 pp); at the level of the state budget, the indicator shows dynamic fluctuations, although at the end of the study period its level is generally 0.5 pp higher than the initial value; at the level of local budgets, it is possible to see a high level of the indicator in budget revenues, with an upward trend (the total positive deviation was 13.3 pp), although it should be noted that in 2022 there was a significant decrease to 30.9%.

Thus, the highest level of fiscal significance of the personal income tax is expected at the level of local budgets, although it has prospects for increasing its impact at all levels.

In support of the above, let's calculate one of the main criteria characterizing the redistribution of GDP through the state budget – the fiscal efficiency of the personal income tax, which is calculated as the ratio of the amount of tax revenues of the tax under study to the gross domestic product of the state (Fig. 1.5).

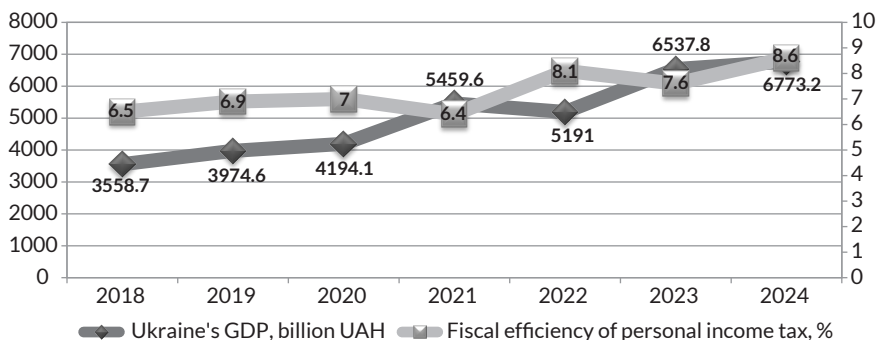


Fig. 1.5 Dynamics of the fiscal efficiency of the personal income tax and the level of GDP in Ukraine in 2018–2024

From 2018 to 2024, the fiscal efficiency of the personal income tax (Fig. 1.5) generally shows upward trends, with an overall positive deviation of 2.1 pp at the end of the study period. At the same time, it is worth noting the downward trends in 2021 to 6.4%, as a reaction to the lockdown and structural changes in the economy, and in 2023, as a result of the continuation of hostilities in the eastern and southern regions.

The fiscal value of the personal income tax in the revenues of the consolidated budget of Ukraine was the highest in 2019–2020 and amounted to 21.4%. However, in 2021–2022, there was a decline in the indicator, and at the end of the study period, its total deviation was -0.2 pp.

Another indicator of the effectiveness of the personal income tax is its efficiency ratio in GDP, which is calculated as the ratio of the fiscal efficiency of the tax to its rate (Fig. 1.6).

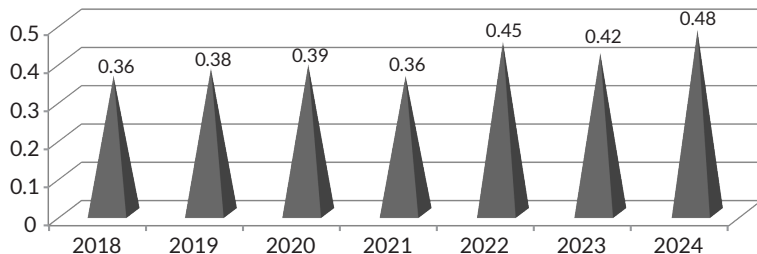


Fig. 1.6 Dynamics of the personal income tax efficiency ratio in GDP in 2018–2024

The personal income tax efficiency ratio in GDP in 2018–2020 (Fig. 1.6) was relatively stable with a slight upward trend. At the same time, the total deviation for the period amounted to 0.03 pp. A similar gap is seen in the decline of the indicator in 2021 and unstable, but generally growing dynamics in 2022–2024. The overall positive deviation of the indicator at the end of the study period compared to the beginning was 0.12 pp.

Overall, it can be concluded that the personal income tax mechanism demonstrated a generally high level of efficiency from a fiscal perspective during the analyzed period. However, it is also important to assess the flexibility of this tax in terms of its responsiveness to changes in economic conditions – namely, through an analysis of tax elasticity. To this end, the elasticity coefficient of personal income tax will be calculated. This coefficient is defined as the ratio of the percentage change in tax revenues to the percentage change in GDP (Fig. 1.7).

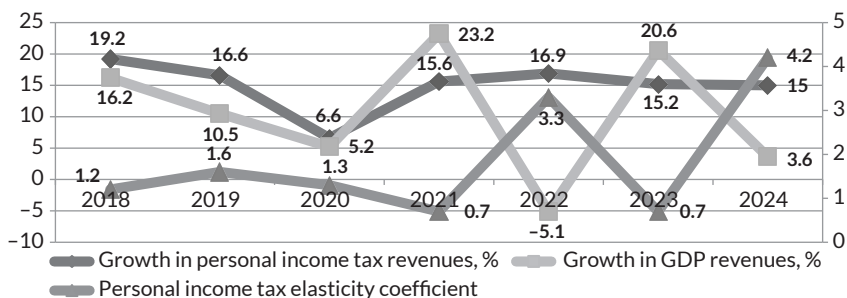


Fig. 1.7 Dynamics of the personal income tax elasticity coefficient in 2018–2024

According to the calculation of the personal income tax elasticity indicator for the period 2018–2024 (**Fig. 1.7**), it should be noted that it is not able to respond to changes in the economic environment and actively influence the production sector only in 2021 and 2023. This is an additional confirmation of the previously identified trends in revenues and estimated figures for this tax, as well as evidence that only deep crisis phenomena can significantly affect the mechanism of the personal income tax.

However, the deep negative structural changes in the economy, the reduction in the number of taxpayers, the decline in revenues and other indicators characterizing the protracted martial law in which Ukraine has been for more than three years indicate that the current mechanism of collecting personal income tax requires finding optimal and modern ways to improve it.

1.4 Directions for improving the mechanism of personal income tax collection in the post-war period

One of the key principles for reforming the personal income tax system in the post-war period should be the incorporation of behavioral aspects into its design and functioning. In particular, behavioral finance theories offer valuable insights into how taxpayers perceive taxation and how these perceptions influence their behavior. As Ukraine enters a phase of post-war reconstruction, the development of a robust tax culture and tax mentality will require an understanding of such behavioral patterns to shape modern and socially grounded approaches to taxation.

According to prospect theory, individuals tend to perceive taxes as losses. The cognitive bias associated with loss aversion is among the most powerful psychological distortions, often leading to tax resistance, including tax avoidance, evasion, and minimization [23]. This resistance is further intensified when the tax system or a specific tax is perceived as unfair. Such perceptions are shaped by the use of heuristics – mental shortcuts individuals apply in decision-making. As suggested by heuristics theory, fairness is a key cognitive element in evaluating taxation [24].

Moreover, many taxpayers struggle to assess the actual impact of taxes on their income and quality of life, especially in the case of indirect taxes, which are embedded in the prices of goods and services. According to the tax perception hypothesis, the payment of indirect taxes is perceived as less burdensome than that of direct taxes – such as personal income tax – due to their less visible nature [25]. This suggests that, to align the personal income tax system with behavioral expectations, its function of justice, particularly social justice, must be reinforced.

Progressive taxation is widely regarded as one of the most effective instruments for reducing social inequality. Behavioral studies show that the perception of fairness associated with progressive taxation is more prevalent among lower-income groups, whereas high-income taxpayers tend to favor proportional (flat-rate) systems [26].

The selection between progressive and proportional (linear) personal income taxation remains a central issue of tax policy, especially in the context of Ukraine's post-war recovery. Progressive taxation, which involves increasing marginal tax rates as income rises, aims to address income inequality and promote a fairer distribution of the tax burden, thereby supporting efforts to alleviate poverty and reduce income disparities [27].

By contrast, the proportional taxation model applies a single tax rate to all taxpayers, regardless of income level. However, empirical data indicate that following its introduction in Ukraine, the share of personal income tax in GDP and total tax revenues declined, potentially pointing to the limited efficiency of this model under national conditions [28].

It is important to acknowledge that both progressive and proportional tax systems have their respective advantages and limitations, which are summarized in **Table 1.5**.

Table 1.5 Advantages and disadvantages of progressive and proportional personal income tax scales

	Progressive scale	Proportional scale
Advantages	Social justice and reducing inequality	Administrative simplicity
	Increase in budget revenues	Stimulating economic activity
	Stimulating economic development by reducing the tax burden at the start	Reducing incentives for tax evasion
Disadvantages	Risk of tax evasion	Lack of social justice
	Administrative complexity	Limited income redistribution
	Potential outflow of capital and high-income professionals	Potential fiscal constraints

Therefore, the introduction of a progressive personal income tax scale in Ukraine during the post-war reconstruction period is an important step to ensure social justice and financial stability. The development of an optimal rate scale should take into account both international experience and the specifics of the Ukrainian economy.

The highest personal income tax rates (**Fig. 1.8**) range from 56.9% in Finland to 12% in Moldova, and the lowest from 5% in Lithuania and Ukraine to 0% in Sweden, the United Kingdom, Germany, France, and Switzerland. And from the above list, Ukraine is among the countries with the lowest taxation [29].

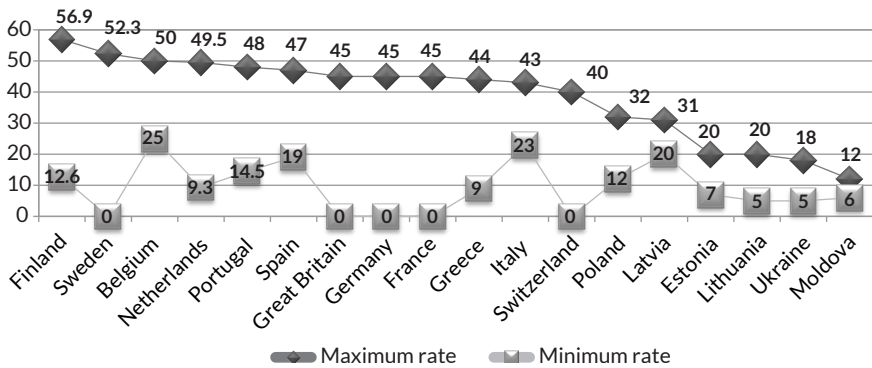


Fig. 1.8 Personal income tax rates in selected European countries as of January 26, 2024

Taking into account international experience and the peculiarities of the Ukrainian economy, it is possible to propose a progressive scale of personal income taxation according to the annual (monthly) amount of income (Fig. 1.9).

Attention should also be given to the introduction of a tax-free minimum for low-income individuals as a measure to protect the most vulnerable segments of the population. As of 2025, the official tax-free minimum income in Ukraine remains fixed at 17 UAH – a nominal value that has not changed since 1996. This amount is primarily used as a reference for calculating administrative fines and other penalties, and it no longer reflects current economic conditions. Moreover, despite its designation, it does not fulfill the function of a genuine tax exemption threshold. In contrast, many European countries actively apply tax-free minimum thresholds as integral components of personal income tax calculations. For example, the annual tax-free minimum is 30,000 PLN in Poland; 10,908 EUR in Germany; 27,840 CZK in the Czech Republic; approximately 5,550 EUR in Spain; 10,777 EUR in France; and approximately 20,000 SEK in Sweden. In Italy, the amount varies depending on marital and family status [30]. Given both international experience and the current socio-economic context in Ukraine, it is advisable to establish a tax-free minimum that provides actual support to low-income earners. It is proposed that this amount be linked to the subsistence minimum for able-bodied persons, which currently stands at 3,028 UAH per month, or 36,336 UAH per year. Setting the tax-free minimum at this level would promote greater fairness in taxation and ensure its alignment with the economic realities faced by Ukrainian citizens.

The proposed progressive approach to personal income taxation will ensure that the above behavioral foundations are taken into account and will help to form an

appropriate level of tax culture among taxpayers, which will become the basis of the nation's tax mentality. It will also be a sign of the realization of the proposed behavioral function.

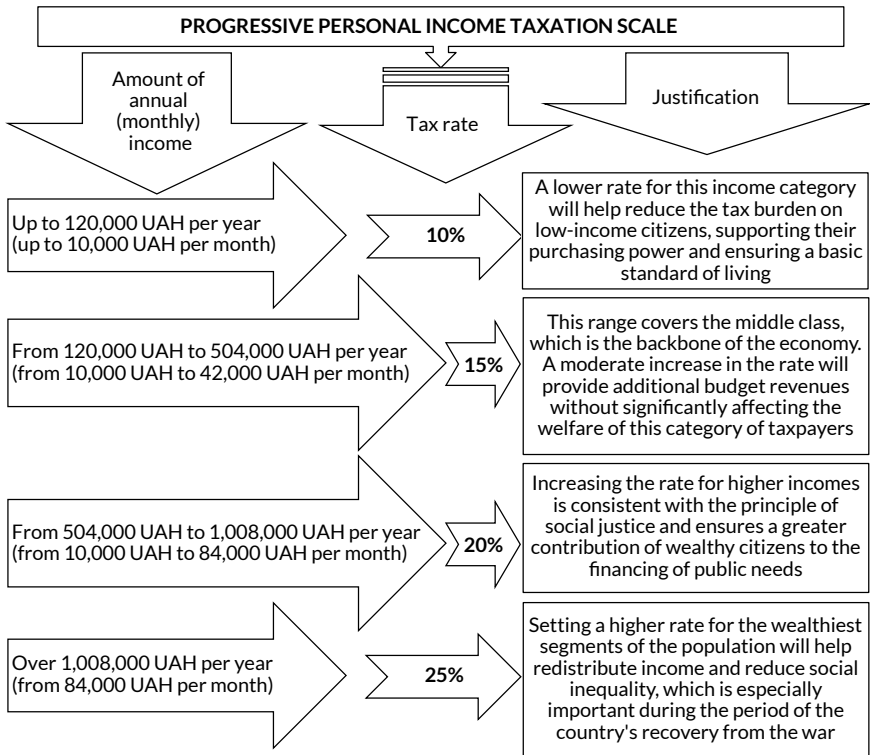


Fig. 1.9 Proposed progressive personal income taxation scale in Ukraine for the post-war period

Reforming the tax system for the post-war perspective should also be based on strengthening digitalization processes, the implementation of which will involve transforming the understanding of the functioning of taxes in particular and the tax system in general [31]. And one of the promising methods of digitalization is called blockchain technology, which will help to transfer data sets without centralized control on the basis of transparency, security and automation. It is being actively promoted in all areas of activity, including even the agricultural sector [32], but in this

study let's focus on the digitalization of personal income tax in the context of meeting the behavioral needs of taxpayers.

Currently, electronic services in Ukraine are available for legal entities and entrepreneurs, but to achieve maximum results, it is necessary to involve individuals, as it is their vision of fairness, efficiency and effectiveness of taxation that shapes the overall trend of tax behavior. Thus, the key areas of digitalization of the personal income tax both now and in the future are as follows (Fig. 1.10).

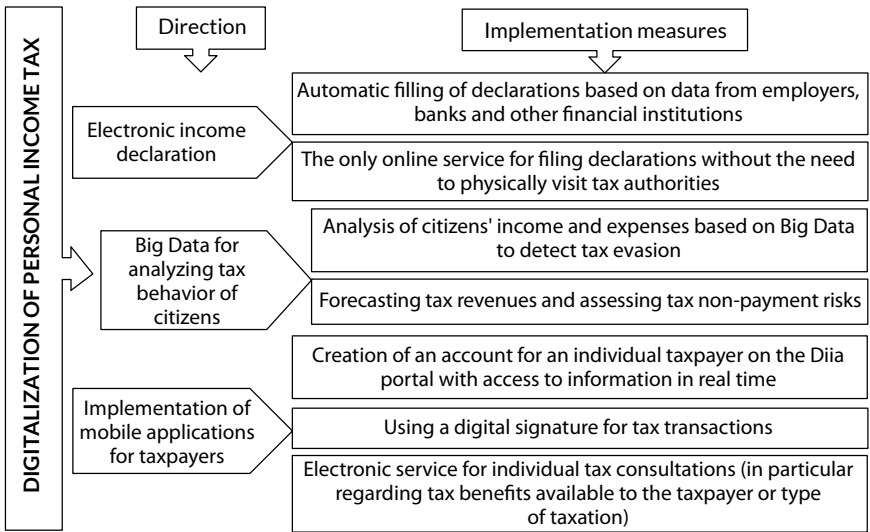


Fig. 1.10 Areas of digitalization of personal income tax in Ukraine for the post-war perspective

The proposed measures for the digitalization of personal income taxation will increase the efficiency of tax administration, help reduce corruption risks, and improve the interaction of taxpayers with the state.

1.5 Conclusions

Personal income taxation in Ukraine currently operates under a proportional model and, overall, demonstrates favorable outcomes in both quantitative and qualitative terms. However, the significant structural disruptions observed in 2020 – due to lockdowns caused by the COVID-19 pandemic – and in 2023 – under martial law

following Russia's full-scale invasion – revealed the need for substantial reform of the existing tax mechanism.

In this context, two priority directions for optimizing the functioning of personal income tax in the post-war period are proposed: the incorporation of behavioral and digitalization aspects. These vectors are conceptualized not only as reform directions but also as potential new functional dimensions of the tax.

The behavioral vector envisions the introduction of a progressive tax scale ranging from 10% to 25%, depending on annual or monthly income levels. It also includes the implementation of an active tax-free minimum, setting at the subsistence level for able-bodied individuals on a monthly and annual basis. These measures aim to restore social justice in taxation and foster positive tax behavior among citizens.

Simultaneously, the digitalization vector addresses the urgent need to modernize tax administration processes. Recommended measures include the implementation of electronic income declarations, the application of Big Data analytics to monitor and assess tax behavior, and the development of mobile applications – particularly on the Diia platform. These tools would enable taxpayers to access information on tax assessments and payments, receive personalized consultations, and exercise control over their tax obligations through electronic digital signatures.

Taken as a whole, these proposed reforms support the formation of a new philosophy of personal income taxation in post-war Ukraine – one that is responsive to the behavioral patterns and expectations of taxpayers, while simultaneously advancing the principles of social justice and enhancing administrative efficiency.

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CHAPTER 2

Digital drivers of business model transformation in the circular economy paradigm

Alla Karnaushenko

Abstract

This study provides a quantitative assessment of the digital drivers influencing business model transformation within the circular economy paradigm, using data from European Union countries. An integrated framework for evaluating the level of digital-circular integration is developed and implemented. The methodological approach includes the construction of a composite index, correlation and regression analyses, K-means clustering, principal component analysis (PCA), and scenario modelling. The study introduces the Integrated Digital Circular Economy Index (IDCEI), which comprises five core indicators reflecting digital intensity and resource efficiency. It is hypothesized that operational digital integration particularly through enterprise resource planning (ERP) systems and the Circular Material Use (CMU) rate are key drivers of the circular transition. The analysis reveals asymmetries in digitalization levels and investment structures across EU member states. The robustness of the IDCEI is validated through empirical verification. Based on digital-circular transformation trajectories, three clusters of countries are identified. The study outlines three development scenarios: intensive digital integration, fragmented implementation, and digital stagnation. A typology of transition models is proposed and visualized, facilitating the identification of transformation pathways. The findings provide a foundation for policy development in digital-environmental transformation, cross-country benchmarking, and integration monitoring. The IDCEI shows potential for broader application in international comparative studies. The scientific contribution lies in the formalization of a novel index for measuring digital-circular transformation and the methodological integration of quantitative and qualitative tools. Research implications include expanding the data set, refining digital indicators (e.g., AI, IoT, DPP), and applying the framework to sectoral analyses.

This chapter is empirical in nature.

Keywords

Circular economy, digital transformation, business models, ERP systems, digital integration, cluster analysis, composite index, sustainable development.

2.1 Introduction

At the current stage of economic development, the significance of the integrated twin transition concept is increasingly evident. This concept entails simultaneous and interlinked transformations along two critical dimensions – ecological and digital – which compel businesses to reconsider their development strategies and fundamentally redesign operational models.

The transition from a linear to a circular economy requires profound transformations in business models, prioritizing reuse, recovery, recycling, and resource efficiency. According to OECD data [1], global material consumption rose from 37 billion tons in 1990 to 88 billion tons in 2017, with projections suggesting it may double by 2060. These figures underscore the urgent need to adopt resource-efficient economic practices.

Within this framework, digital technologies play a crucial role. They enhance supply chain transparency and traceability, enable advanced product lifecycle analytics, support personalized services, and facilitate the adoption of service-oriented business models. Additionally, digital solutions reduce communication and coordination barriers among value chain stakeholders, promote partnerships, and foster the development of shared services and innovative business models.

However, research indicates that service-based circular economy models do not always guarantee sustainability due to potential risks, such as load redistribution and unintended consequences.

As a result, it is essential to examine the digital drivers behind business model transformation, as they shape both the pace and direction of the transition to the new economic paradigm. Moreover, it is important to assess the practical implications of these changes – specifically, the adaptability of business models to circular economy principles across operational, innovative, and strategic dimensions.

Amid growing pressure from consumers, governments, and civil society, businesses are increasingly required to embrace new value creation models characterized by resource efficiency, renewability, and circularity. Digital technologies are critical enablers of this transformation, essential for ensuring the sustainability and competitiveness of contemporary business models.

In this context, developing an integrated indicator capable of quantitatively assessing the level of digital – circular integration becomes especially important.

To address this need, the author proposes the Index of Digital Circular Economy Integration (IDCEI), a composite measure designed to evaluate the degree of transformation in business environments toward a digitally oriented circular economy. The methodological foundations for constructing the IDCEI are detailed in Paragraph 2.2.

Current academic literature demonstrates a growing interest in digitalization within the context of circular transformation. For instance, D. Chiaroni, P. D. Vecchio, D. Peck, A. Urbinati, D. Vrontis identify digitalization as a key enabler of circularity, capable of reshaping enterprise operations, product design, and consumer behavior [3]. Similarly, G. Bressanelli, N. Saccani, and M. Perona examine the sustainability of digitally servitized business models through a "what-if" systemic approach, highlighting potential risks associated with load redistribution and unintended consequences [2].

A. Pagoropoulos, D. Pigosso, and T. McAloone underscore the capacity of digital technologies to enhance resource efficiency and generate new business model opportunities [4]. In a related vein, M. Antikainen, T. Uusitalo, and P. Kivikytö-Reponen emphasize the role of digital solutions, particularly Big Data and analytics in optimizing resource flows and improving product traceability [5].

A systematic review by C. Chauhan, V. Parida, and A. Dhir maps out technologies that support circularity, drawing attention to the gap between theoretical contributions and practical implementation challenges [6]. P. Rosa, C. Sassanelli, and S. Terzi propose archetypes and classification frameworks for circular business models in digitally enabled contexts [7]. In parallel, V. Ranta, L. Aarikka-Stenroos, and J.-M. Väisänen explore how digital technologies can help overcome transition barriers and foster innovation [8], while F. Lüdeke-Freund, S. Gold, and N. Bocken develop a typology of circular economy business models, with a particular focus on the enabling role of digital tools [9].

In the context of digital transformation of business models, particularly under conditions of instability and post-crisis recovery, agent-based modeling and intelligent optimization algorithms play a critical role. T. Cherniavska, N. Tanklevska, B. Cherniavskiy present several approaches that highlight the potential of digital technologies for optimizing vital systems in wartime and post-war scenarios. Their studies include the development of an agent-based decision-making system for managing water resource remediation in the Kherson region [10], an architecture-oriented agent-based model for optimizing transport evacuation and emergency medical assistance during the war in Ukraine [11], and the application of bee colony algorithms for medical logistics optimization in emergency and post-conflict settings [12]. These works demonstrate how AI-driven and agent-based solutions can support the adaptation and resilience of complex systems in the face of disruption. Such approaches offer valuable insights for circular economy strategies, which require flexible, sustainable, and digitally enabled business models to respond

effectively to environmental and systemic challenges. Y. Kyrlov, V. Hranovska, V. Savchenko, L. Kononenko, O. Gai, S. Kononenko explore sustainable rural development through the application of digital and nanotechnologies in education and business, highlighting their potential to foster innovation and support circular business model adaptation in rural areas [13]. Similarly, L. Kononenko, O. Atamas, H. Nazarova, Y. Selishcheva, S. Kononenko examine tax optimization for small agricultural producers via innovative-integrated structures, contributing to the development of more efficient and sustainable business models [14]. A. Karnaushenko, N. Tanklevska, T. Povod, L. Kononenko, V. Savchenko highlight the role of blockchain technology in transforming agricultural business models toward circularity, emphasizing its potential to support transparency and traceability in supply chains [15].

Despite the increasing relevance of this topic, the specific impacts of digital technologies on the integration of circular economy principles – both at the firm level and across industry sectors – remain underexplored. In particular, limited scholarly attention has been paid to how digital technologies restructure business models, redefine value creation logic, and transform customer engagement. Moreover, it remains unclear to what extent firms can effectively embed circularity into both existing and newly developed business models.

Consequently, conducting empirical research aimed at identifying the digital drivers of business model transformation within the circular economy paradigm while analyzing sector-specific dynamics, exploring implementation barriers, and assessing the potential for achieving sustainable competitive advantage appears both timely and relevant.

The aim of this study is to quantitatively evaluate the digital drivers influencing business model transformation within the circular economy paradigm, drawing on evidence from European Union countries. To this end, the research develops a composite indicator – the Index of Digital Circular Economy Integration (IDCEI) – analyses its structural components, conducts cross-national comparisons, and identifies institutional and sector-specific characteristics that underpin the transition towards digital circularity.

Achieving this objective requires the verification of several scientific assumptions that clarify the causal relationships between levels of digitalization, investment activity, and the degree of circular business model implementation. Accordingly, the following hypotheses have been formulated to reflect the anticipated structural interdependencies among key factors driving digital – circular transformation, and to facilitate empirical validation of the study's conceptual framework:

H1: there is statistically significant variability among EU countries regarding the level of digital-circular transformation of business models, attributable to differences in institutional, economic, and technological readiness.

H2: a higher degree of digitalization particularly through the adoption of ERP systems and artificial intelligence (AI) is positively correlated with the extent to which circular practices are embedded within business models.

H3: the volume of investments directed towards the circular economy constitutes a critical factor in accelerating digital-circular transformation; however, investment alone does not ensure a high level of integration in the absence of well-developed digital infrastructure.

H4: the digital – circular transformation of business models within EU countries is uneven, owing to varying degrees of technological maturity, economic capacity, and alignment with sustainable development policies.

2.2 Research methodology

2.2.1 Methodological framework

The methodological framework of this study is grounded in an interdisciplinary approach that integrates the concepts of digital transformation, business model innovation, and circular economy principles. To address the research objectives, a comprehensive methodological toolkit was employed, incorporating both qualitative and quantitative analytical techniques.

A systematic review of recent scientific literature was conducted using databases such as ScienceDirect, the OECD iLibrary, and Google Scholar. The aim was to identify key digital drivers of circular transformation and to establish a robust theoretical and analytical foundation. Sources were selected using relevant keywords, including "circular economy business models", "digital transformation", "servitization", and "resource efficiency".

The empirical analysis draws on official statistical data from Eurostat, the OECD, and the World Bank, encompassing a range of digital and circular economy indicators for European Union member states. These data were used to construct the Integrated Digital Circular Economy Index (IDCEI), a composite measure designed to capture the extent of digital-circular transformation.

To enable a more in-depth analysis, the following methods were applied:

1. Correlation analysis was carried out to examine the interrelationships among key variables.
2. A multiple linear regression model was estimated using the ordinary least squares (OLS) method to assess the relative impact of each factor on the IDCEI score.

3. K-means clustering was employed to identify homogeneous groups of countries based on their levels of digital – circular maturity.

4. Principal Component Analysis (PCA) was utilized to visualize the spatial distribution of countries within a multidimensional analytical framework.

5. Scenario analysis was incorporated to simulate potential transformation trajectories of business models, accounting for institutional and sector-specific contexts.

This integrated methodological approach enabled empirical testing of the research hypotheses (H1–H4) and facilitated a comprehensive characterization of the digital-circular transformation process in contemporary business models.

2.2.2 Conceptual foundations of the Integrated Digital Circular Economy Index (IDCEI)

The Integrated Digital Circular Economy Index (IDCEI) is a composite indicator designed to quantitatively assess the extent to which digital technologies are integrated with circular economy principles within national economies. The index captures the degree to which countries are adapting their business models to align with contemporary sustainability imperatives, viewing digitalization not as an end in itself, but as a strategic enabler of resource efficiency, renewability, and circularity.

Employing a composite index methodology, the IDCEI enables cross-national comparisons of digital – circular maturity, thereby identifying leading performers, laggards, and structural disparities in integrated transformation processes. In addition, the index supports policy benchmarking, strategic monitoring of progress on key indicators, and the identification of areas requiring enhanced institutional capacity or targeted investment. As such, the IDCEI serves both diagnostic and prognostic functions, reframing digital transformation from a purely technological endeavor to a foundational pillar of sustainable economic development within the circular economy paradigm.

The IDCEI comprises the following five indicators:

- digital intensity of enterprises (%) – representing the overall level of digitalization across businesses;
- share of enterprises using ERP systems (%) – reflecting the depth of digital integration in internal operational processes;
- investment in the circular economy as a share of GDP (%) – indicating governmental financial commitment to the circular transition;
- circular Material Use Rate (CMU, %) – measuring the proportion of secondary materials reused in production cycles;

– waste generated per unit of GDP (inverse indicator) – serving as a proxy for eco-efficiency.

To ensure cross-country comparability, all component indicators were normalized using the Min-Max normalization method, a linear rescaling technique that transforms data into a [0,1] range

$$x_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}}. \quad (2.1)$$

For the indicator "Generation of waste excluding major mineral wastes per unit of GDP", inverse normalization was applied, as lower values signify higher levels of resource efficiency. This transformation ensures that all indicators follow the same directional logic, where higher scores reflect more advanced digital-circular integration (formula (2.2))

$$x_{inv.norm} = 1 - \frac{x - x_{min}}{x_{max} - x_{min}}. \quad (2.2)$$

The calculation of the Integrated Digital Circular Economy Index (IDCEI) is expressed as a weighted sum of the normalized component indicators, thereby capturing the composite nature of the index

$$IDCEI = 0.2 \cdot ERP_{norm} + 0.2 \cdot Digital_{norm} + 0.2 \cdot Invest_{norm} + 0.25 \cdot CMU_{norm} + 0.15 \cdot (1 - Waste_{norm}). \quad (2.3)$$

The resulting index values range from 0 (indicating the lowest level of transformation) to 1 (representing the highest level), thereby enabling meaningful comparisons and benchmarking across countries.

Weighting coefficients for constructing the IDCEI were determined through analytical weighting, taking into account strategic priorities defined by the European Union under the European Green Deal and the Circular Economy Action Plan. The adopted weighting structure reflects both the functional importance of each indicator in business model transformation and their representativeness in cross-country comparisons.

Specifically, the digital component, accounting for a combined 40%, comprises two indicators: the share of enterprises using ERP systems (weighted at 20%) and the Digital Intensity Index of enterprises (also weighted at 20%). ERP systems play a pivotal role in the digital integration of internal processes, particularly resource and logistics management – essential aspects for implementing circularity principles. Meanwhile, the Digital Intensity Index captures the overall readiness of the business

environment to adopt advanced technological solutions such as artificial intelligence, cloud computing, and analytics.

The overall circular component constitutes 45% of the total weighting. Within this component, the Circular Material Use Rate (CMU) – considered a key indicator of circularity in European statistical frameworks – holds a 25% weighting. A further 20% is allocated to investments in the circular economy as a share of GDP, reflecting national financial commitments to sustainable development and the innovative transformation of production processes.

The eco-efficiency indicator – generation of waste excluding major mineral wastes per unit of GDP – is included using inverse normalization, with a weighting of 15%. Although this indicator primarily reflects the outcomes of resource use rather than directly driving transformation, it signifies progress in reducing waste generation and pollution, thereby justifying its moderate weight in the index structure.

Therefore, the proposed weighting scheme effectively balances the technological and environmental dimensions of transformation, capturing both potential capacity and actual performance in realizing a digitally driven circular development model.

2.3 Results

2.3.1 Investments in the circular economy

European Union investments in digital technologies are crucial for accelerating the transition to a circular economy. Under the EU's Multiannual Financial Framework for 2021–2027, significant resources are allocated to digital transformation and the development of Industry 4.0, including support for research in artificial intelligence, cybersecurity, and advanced digital skills. Such investments create the necessary conditions for implementing circular business models by promoting the broader adoption of digital solutions across both economic activities and societal practices [16]. Specifically, the EU plans to mobilize over 100 billion EUR to support regions that require substantial adaptation to the green economy, including the decarbonization of the energy sector and the integration of circular economy practices [17, 18] (**Fig. 2.1**).

To evaluate the impact of investments on the development of the circular economy across EU countries, generalized data on private investments in circular economy sectors for the period 2019–2023 are presented below (**Table 2.1**). Countries were selected based on their total investment volumes in 2023 and categorized into three distinct groups: leaders (Germany, France, the Netherlands, Italy), moderate performers (e.g. Czech Republic, Spain, Finland), and countries with the lowest

investment levels (Cyprus, Latvia, Malta, Bulgaria, Greece). This classification facilitates the identification of structural differences between countries and supports a more detailed analysis of the factors underlying uneven investment distribution within the EU's circular economy landscape.

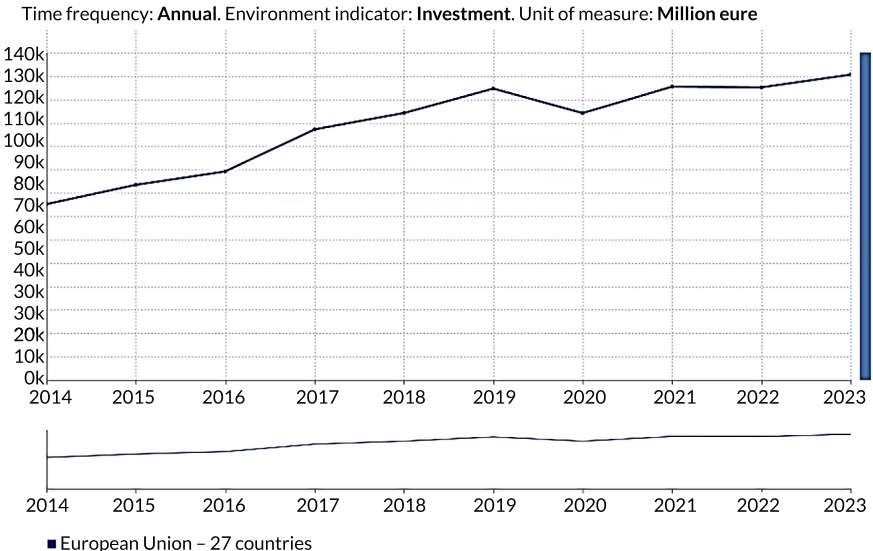


Fig. 2.1 Private investment to circular economy sectors
Source: [17, 18]

Between 2019 and 2023, investment dynamics in circular economy sectors across EU countries were mixed. An analysis of the 15 selected countries reveals sustained investment growth in certain states, alongside notable fluctuations or declines in others. **Table 2.1** illustrates trends in private investment in circular economy sectors across EU countries during the 2019–2023 period. The data highlight a general upward trend in investment, while also revealing significant heterogeneity among member states. The highest growth rates were recorded in Finland (+29.6%), Luxembourg (+23.5%), and the Czech Republic (+10.0%), reflecting the successful implementation of sustainability policies, government support for innovation, and strong private sector readiness to adopt circular practices. Moderate investment growth was observed in France (+8.1%), Romania (+6.3%), and Germany (+13.4%), indicating steady development within their respective circular economy sectors.

Table 2.1 Dynamics of investments in the circular economy by EU country (2019–2023)

Country	2019	2020	2021	2022	2023	Change 2023 vs 2019 (%)
Germany	34831	35255	37147	37342	39500	13.40
France	20832	21993	23523	21961	22515	8.08
Netherlands	11346	8666	10360	10740	11229	–1.03
Italy	13118	8142	9734	9861	10173	–22.45
Czech Republic	1618	1557	1816	1732	1780	10.01
Romania	1098	940	1329	1135	1167	6.28
Hungary	1120	1009	1040	1095	1145	2.23
Luxembourg	858	721	1033	1016	1060	23.54
Finland	759	773	1389	957	984	29.64
Cyprus	75	68	129	66	68	–9.33
Malta	93	76	68	80	83	–10.75
Slovenia	146	133	169	126	127	–13.01
Greece	370	327	527	203	174	–52.97
Latvia	349	215	205	229	234	–32.95
Other countries	33864	30669	33156	34225	35365	4.40

Source: [17, 18]

Conversely, several countries experienced a reduction in investment levels. The sharpest declines were recorded in Greece (–52.9%) and Latvia (–32.9%), alongside negative trends in Italy (–22.5%), Slovenia (–13.0%), Malta (–10.8%), and Cyprus (–9.3%), necessitating further analysis of national strategies and priorities related to the green transition.

Thus, the results indicate growing investment activity in selected EU member states within the circular economy, while simultaneously underscoring persistent structural disparities. These findings highlight the need for targeted support policies to address negative investment trends and promote deeper integration of circular principles into economic planning at both national and supranational levels.

Governmental support plays a critical role in fostering investments in the circular economy. For example, France launched the Eco-responsible Digital Acceleration programme under the France 2030 plan, providing financing for projects focused on eco-design and digital product lifecycle extension [19]. In 2023, Germany adopted the National Circular Economy Strategy (NCES), prioritizing digital solutions such as resource tracking and introducing a Digital Product Passport for industry [20, 21]. Such state-level initiatives incentivize the private sector to invest in relevant technologies and infrastructure.

Overall, these findings demonstrate not only the structural disparities among EU countries in adopting circular economy models but also emphasize the need for adaptive support and stimulation policies tailored to each member state's economic, regional, and technological specificities.

Regarding Ukraine, the State Statistics Service of Ukraine does not report this indicator in the Eurostat format [21], and investments in circular solutions remain relatively low.

2.3.2 Calculation of the Integrated Digital Circular Economy Index (IDCEI) based on statistical indicators

The Integrated Digital Circular Economy Index (IDCEI), developed by the author, was applied to analyze the current state of digital-circular maturity of business models in selected EU countries. The index is constructed from the following five indicators:

- digital intensity level of enterprises (Digital);
- proportion of enterprises using ERP systems (ERP);
- investment in the circular economy as a share of GDP (Invest);
- circular material use rate (CMU);
- generation of waste excluding major mineral wastes per unit of GDP (Waste).

Within the research, Min-Max normalization was employed to standardize the primary indicators. Notably, the indicator "Generation of waste excluding major mineral wastes per unit of GDP" was inversely normalized due to its negative correlation with resource efficiency. The weighting of each indicator was determined analytically, taking into account the strategic priorities outlined in EU policy frameworks related to the circular economy and digital transformation.

Table 2.2 presents the input data and the final IDCEI calculations for the countries included in the sample described in Paragraph 2.3.1.

The top performers in terms of digital-circular integration are the Netherlands, Luxembourg, and Malta, which demonstrate high levels of both digital maturity and circularity. At the lower end of the ranking are Romania, Latvia, and Hungary, reflecting structural constraints in circular economy investments and slow progress in digitalization. The corresponding ranking is visualized in **Fig. 2.2**.

The results obtained enable a comparative assessment of countries based on their readiness to develop digitally enabled circular business models. Moreover, the IDCEI can serve as a foundational tool for the ongoing monitoring of transformation dynamics towards digital circularity.

Table 2.2 Input data and results of the Integrated Digital Circular Economy Index for 2023

Country	Digital intensity level of enterprises (Digital), %	Proportion of enterprises using ERP systems (ERP), %	Investment in Circular Economy as a Share of GDP (Invest), %	Circular material use rate (CMU), %	Generation of waste excluding major mineral wastes per GDP unit (Waste)	IDCEI
Germany	62	43.7	0.92	13.9	48	0.599
France	53	47.3	0.77	17.6	43	0.602
Netherlands	79	49.9	0.99	30.6	56	0.834
Italy	61	42.2	0.46	20.8	66	0.526
Czech Republic	51	29.0	0.56	12.8	81	0.336
Romania	28	22.6	0.33	1.3	110	0.024
Hungary	54	35.2	0.56	5.9	110	0.305
Luxembourg	59	43.8	1.23	10.2	31	0.656
Finland	86	56.9	0.36	2.4	46	0.561
Cyprus	68	41.6	0.2	5.4	71	0.358
Malta	77	46.5	0.37	19.8	44	0.623
Slovenia	52	37.0	0.19	8.8	57	0.378
Greece	44	45.3	0.07	5.2	70	0.410
Latvia	49	34.0	0.58	5.0	85	0.288
EU Average	59	43.3	0.34	11.8	60	-

Source: [17, 18, 22, 23]

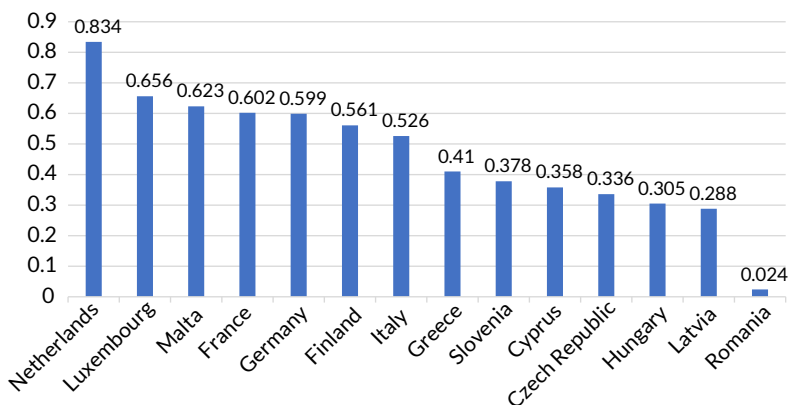


Fig. 2.2 Ranking results of the Integrated Digital Circular Economy Index for 2023
Source: visualized by the author of this study

Simultaneously, the quantitative assessment of digital-circular integration through the IDCEI provides a basis for conducting a qualitative analysis of potential scenarios for further business model transformation. Given the high degree of variability across countries, sectors, and institutional contexts, the application of a scenario-based approach is deemed appropriate as an analytical tool for forecasting possible development trajectories of a digitally oriented circular economy in both the medium- and long-term perspectives.

2.3.3 Empirical verification of the Integrated Digital Circular Economy Index (IDCEI) structure

To validate the methodological soundness of the constructed Integrated Digital Circular Economy Index (IDCEI), a correlation and regression analysis [24] of its constituent indicators was conducted. Given that the IDCEI is a composite indicator aggregating five variables, it is essential to empirically test which components contribute most to inter-country variability and to assess the extent to which the empirical structure aligns with the theoretically assigned weighting scheme.

This approach does not aim to predict IDCEI values per se since they are derived from a linear combination of normalized indicators – but rather to evaluate the actual statistical significance of each component in shaping the index. In doing so, the robustness and validity of the index's construction are empirically verified.

The Ordinary Least Squares (OLS) method was employed to estimate the contribution of each indicator to the overall variance in IDCEI scores across countries. The dependent variable was the IDCEI score, while the independent variables were the five components included in the index. The results are presented in **Table 2.3**.

The results presented in **Table 2.3** suggest that the most substantial contributions to the variance in the IDCEI are made by the following predictors:

- CMU (Circular Material Use Rate) is the most influential variable ($p < 0.001$), highlighting the centrality of resource recirculation in digital-circular integration;
- ERP systems play a critical role in operational digitalization ($p = 0.001$), underscoring the importance of internal process integration;
- Invest (investment in the circular economy) also demonstrates strong statistical significance ($p = 0.002$), reflecting the level of resource commitment to structural transition;
- Waste is negatively associated with the IDCEI ($p = 0.032$), emphasizing the inverse relationship between inefficiencies in value creation chains and digital-circular maturity.

Table 2.3 Results of the OLS regression model for IDCEI

Variable	Coefficient	Std. error	t-statistic	p-value	95% confidence interval
Const	-0.0907	0.104	-0.875	0.407	[-0.330; 0.148]
Digital	+0.0008	0.001	0.844	0.423	[-0.001; 0.003]
ERP	+0.0106	0.002	5.005	0.001	[0.006; 0.015]
Invest	+0.1406	0.031	4.539	0.002	[0.069; 0.212]
CMU	+0.0087	0.001	6.787	0.000	[0.006; 0.012]
Waste	-0.0016	0.001	-2.591	0.032	[-0.003; -0.000]

Source: developed by the author of this study

Note: Model diagnostics indicate a high level of explanatory power: $R^2 = 0.986$, adjusted $R^2 = 0.977$, suggesting that the model explains 98.6% of the variance in the IDCEI. The F-statistic = 110.3 with a p-value < 0.001 confirms the overall statistical significance of the regression model

Conversely, the digital variable is not statistically significant ($p = 0.423$), indicating relatively weak explanatory power when decoupled from more advanced digital integration mechanisms, such as ERP.

To further explore the interrelationships among variables, a correlation matrix was developed and is presented in **Table 2.4**.

Table 2.4 Correlation matrix between the IDCEI and its component indicators

	Digital	ERP	Invest	CMU	Waste	IDCEI
Digital	1.00	0.83	0.26	0.50	-0.61	0.58
ERP	0.83	1.00	0.48	0.73	-0.73	0.85
Invest	0.26	0.48	1.00	0.67	-0.58	0.84
CMU	0.50	0.73	0.67	1.00	-0.77	0.93
Waste	-0.61	-0.73	-0.58	-0.77	1.00	-0.84
IDCEI	0.58	0.85	0.84	0.93	-0.84	1.00

Source: calculated by the author of this study

The analysis revealed a strong positive correlation between the IDCEI and the indicators CMU, ERP, and Invest, as well as a significant inverse correlation with Waste. These results confirm that the index structure effectively reflects cross-country differences in the integration of digital and circular approaches. In contrast, the moderate correlation between Digital and the IDCEI (0.58) indicates the need for further refinement of the digital component – particularly through the incorporation of specific technologies such as artificial intelligence (AI), the Internet of Things (IoT), or Digital Product Passports (DPP).

The correlation and regression analysis provided robust empirical support for the proposed structure of the Integrated Digital Circular Economy Index. The most influential variables in explaining IDCEI variance are those assigned the highest weights in the index methodology (CMU, ERP, Invest), thereby validating both the theoretical assumptions and the applied weighting scheme. These findings suggest that the IDCEI serves as a reliable tool for assessing the structural foundations of digital-circular business model transformation across EU member states.

Furthermore, the observed variability in IDCEI scores among countries points to significant structural asymmetries in their transformation trajectories. To identify these patterns and classify countries according to their level of digital-circular maturity, a cluster analysis was conducted. This approach not only enables the identification of countries with similar transition profiles but also provides a quantitative basis for topologizing transformation models at the supranational level.

2.3.4 Cluster analysis of the digital-circular transformation of business models

To identify typical groups of countries based on their level of digital-circular transformation, the K-means clustering method was applied. This technique enables the automatic grouping of countries according to the similarity of their digital and circular characteristics and is particularly suitable for detecting latent structures in multidimensional datasets.

The analysis incorporated the five key indicators that constitute the IDCEI: Digital, ERP, Invest, CMU, and Waste. All variables were pre-processed using normalization techniques to ensure equal contribution to the clustering process.

To determine the optimal number of clusters, the elbow method was employed. This approach involves evaluating the dynamics of inertia (i.e. within-cluster variance) across different values of k (number of clusters), ranging from 1 to 10. The resulting elbow point – where the rate of inertia reduction begins to plateau – indicates the most appropriate cluster count. The outcomes of this procedure are visualized in **Fig. 2.3, 2.4**.

Fig. 2.4 illustrates a distinct inflection point at $k = 3$, indicating that the optimal number of clusters is three. Beyond this point, the reduction in within-cluster inertia becomes marginal, suggesting limited benefits from further segmentation. Based on this result, the countries were grouped into three clusters reflecting typical trajectories of digital-circular transformation:

Cluster 0 – leaders in digital-circular transformation: these countries demonstrate high levels of digital maturity, extensive adoption of ERP systems, substantial

investment in circular economy initiatives, high Circular Material Use (CMU) rates, and low levels of waste generation. Collectively, these features reflect an advanced stage of twin transition implementation.

Cluster 1 – structurally lagging countries: this group is characterized by low levels of digitalization, limited ERP adoption, high waste intensity, and the lowest IDCEI values. Such a profile indicates systemic underperformance in both digital and circular domains.

Cluster 2 – digitally active but circularly underdeveloped countries: despite relatively high digital intensity, these countries report low CMU rates and limited circular economy investment. This imbalance constrains the overall depth of their business model transformation.

Step-by-step K-means clustering visualization ($k = 1$ to 10)

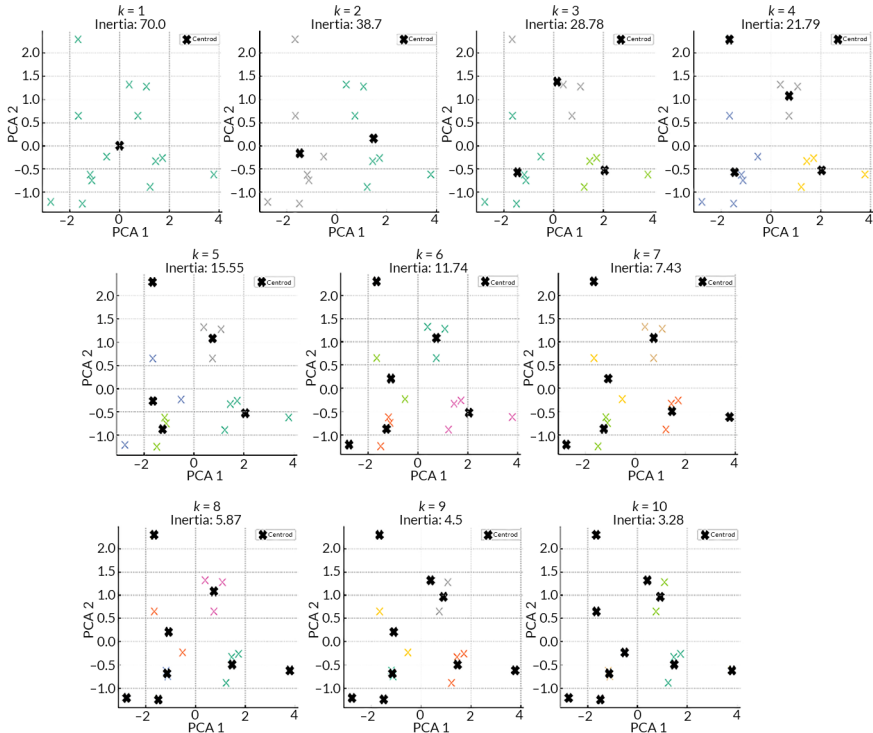


Fig. 2.3 Visualization of country clustering using the K-means method ($k = 1-10$)
Source: visualized and calculated by the author of this study

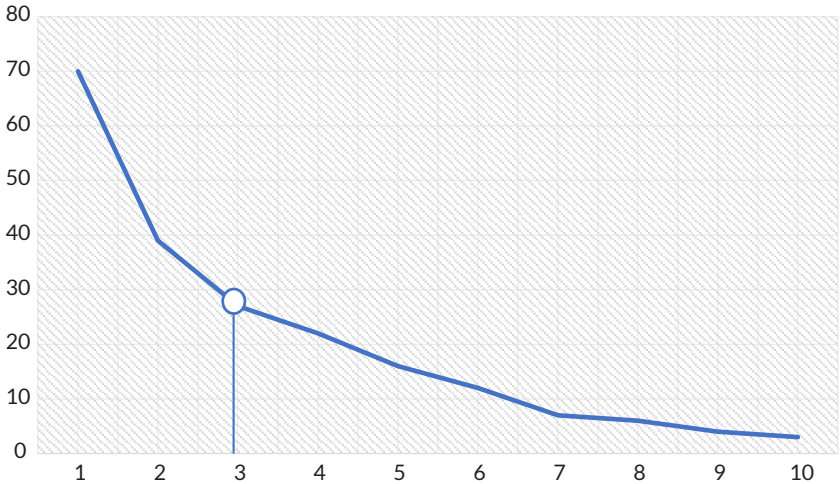


Fig. 2.4 Elbow method for determining the optimal number of clusters
Source: visualized by the author of this study

The average values of the key indicators for each cluster are summarized in **Table 2.5**.

Table 2.5 Average values of digital and circular indicators across identified clusters							
Cluster	Digital	ERP	Invest	CMU	Waste	IDCEI	Number of countries
0	65.2	45.6	0.79	18.8	48.0	0.64	5
1	45.5	30.2	0.51	6.25	96.5	0.24	5
2	71.2	45.1	0.20	5.45	53.3	0.43	4

Source: calculated by the author of this study

For improved interpretability of the results, dimensionality reduction was performed using Principal Component Analysis (PCA). **Fig. 2.5** presents the spatial distribution of each country along the PCA1 and PCA2 axes, according to their respective cluster membership.

The cluster analysis confirmed the existence of significant cross-country disparities in the level of digital-circular transformation. The classification of countries into three distinct clusters enables the formalization of typical adaptation scenarios to the emerging economic paradigm and supports the development of differentiated strategies for fostering digital-circular progress.

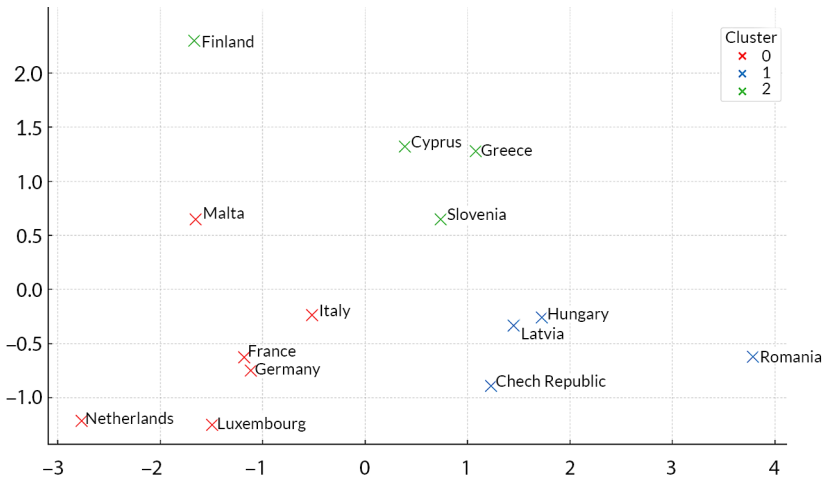


Fig. 2.5 Visualization of country clusters in the principal component space (PCA1-PCA2)
Source: visualized by the author of this study

At the same time, the quantitative assessment of digital-circular integration through the IDCEI provides a solid foundation for a qualitative exploration of potential future transformation pathways in business models. Given the high degree of variation across countries, sectors, and institutional contexts, the application of a scenario-based approach is justified as an analytical tool for forecasting possible trajectories in the evolution of a digitally enabled circular economy, both in the medium- and long-term perspective.

2.3.5 Scenario analysis of business model transformation within the digital-circular paradigm

In the context of digital transformation, analyzing the potential trajectories of business model development under the influence of digital technologies aligned with circularity principles is of critical importance. Based on the quantitative assessment provided by the IDCEI, a scenario-based approach is employed to model possible adaptation pathways of business models in response to the twin transition – digital and environmental.

The scenario analysis includes three variants – Optimistic: intensive digital integration, Moderate: fragmented implementation, and Pessimistic: Digital stagnation –

each reflecting different levels of institutional support, digital maturity, and capacity for integrating circular practices:

Scenario 1: Optimistic – intensive digital integration.

This scenario envisions the comprehensive implementation of key digital technologies, such as ERP systems for internal integration, artificial intelligence (AI) for data optimization, the Internet of Things (IoT) for resource monitoring, and Digital Product Passports (DPPs) for lifecycle transparency and management. These are supported by targeted governmental initiatives and robust institutional frameworks.

Business models evolve towards service-oriented structures, enabling flexibility, enhanced resource efficiency, and systemic circularity, in which reuse and recovery become central elements. This trajectory closely aligns with the strategic priorities of the European Green Deal [25], Digital Europe [26], and Horizon Europe [27].

Under this scenario, national performance converges with that of leading countries in 2023, such as the Netherlands and Germany, which exemplify advanced integration of digital technologies and circular practices. Industry demonstrates high ERP coverage (up to 80%), broad DPP adoption, and Circular Material Use Rates exceeding 30% [28]. In the construction sector, Building Information Modelling (BIM 5D) is widely adopted, along with digital material reuse platforms such as France's Circular Building Hub [29]. Agriculture becomes "smart", leveraging IoT, sensors, and AgTech platforms, resulting in waste reduction exceeding 17% [30].

Scenario 2: Moderate – fragmented implementation.

This scenario reflects the selective adoption of digital solutions, primarily by large enterprises, while small and medium-sized enterprises (SMEs) remain largely outside the scope of transformation. Governmental policies promoting circularity are limited in scope and often temporary.

Industrial ERP coverage ranges between 40–50% [31]. Logistics systems are partially automated but lack standardized digital frameworks for circularity. In construction, BIM is used without circular modules, and there is no system for material tracking. Agricultural digitalization is limited to large agribusinesses, with minimal support for SMEs, which continue to face barriers to financing and infrastructure access [32].

Scenario 3: Pessimistic – digital stagnation.

In the absence of political will and adequate technological infrastructure, digitalization and circularity principles fail to integrate into business models, and linear production systems persist. Circular practices are sporadic and confined to niche initiatives.

Industry lacks DPPs, ERP implementation remains below 30%, and waste per unit of GDP continues to rise. The construction sector relies heavily on primary

materials, with no digital tools or lifecycle monitoring in place. Agriculture remains traditional, with minimal or no digital integration, resource-intensive methods, and heightened ecological risks.

2.4 Conclusion

The objective of this study was successfully achieved: the digital drivers of business model transformation within the circular economy paradigm were quantitatively assessed using the proposed Integrated Digital Circular Economy Index (IDCEI). The methodology involved the construction of the composite index, its empirical verification, country-level clustering, and the development of transformation scenarios.

The IDCEI enabled a comprehensive assessment of the extent to which digital and circular attributes are integrated within national economies. The results of the correlation – regression analysis confirmed the analytical validity of the index structure. The most influential factors were identified as the Circular Material Use Rate (CMU), ERP system integration, investment in the circular economy, and eco-efficiency performance. By contrast, general digital intensity appeared less significant in the absence of deep operational integration of digital technologies.

Accordingly, all four research hypotheses (H1–H4) were empirically validated. The findings revealed statistically significant cross-country differences in digital-circular maturity, highlighted the crucial role of digitalization (particularly ERP integration) in supporting circular practices, and emphasized the importance of aligning digital infrastructure with investment capacity to ensure successful transformation.

The cluster analysis revealed three distinct development trajectories:

- Cluster 0 includes countries with high digital-circular maturity;
- Cluster 1 comprises structurally lagging economies with limited integration of digital and circular solutions;
- Cluster 2 represents digitally advanced countries with unrealized circular potential, calling for investment reorientation towards resource sustainability.

Scenario analysis demonstrated that the future trajectory of digital-circular transformation depends on institutional readiness, strategic commitment, and the capacity to embed digital innovation into sustainable business models. The optimistic scenario envisions the integration of ERP, IoT, AI, and Digital Product Passports (DPPs); the pessimistic scenario illustrates the risk of stagnation associated with continued reliance on linear production models.

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CHAPTER 3

Digitalization of crisis management remediation: assessment of implementation and development prospects

Bohdan Cherniavskyi

Abstract

The first quarter of the 21st century has been marked by the growth in the scale and complexity of emergencies, ranging from global climate disasters to full-scale military conflicts. All of this has created an acute need to shift from traditional crisis management methods to intelligent digital systems capable of responding rapidly, processing vast arrays of heterogeneous data, and coordinating the actions of all participants in real time. In this context, remediation in the modern world has already been established as a multifunctional process that combines the restoration of the ecological environment with the revival of socio-economic activity on the cleaned, reconstructed, and restored territory. Today, successful remediation serves not only an environmental purpose but also stimulates the return of the population, the development of entrepreneurial entities, the attraction of investments, and the strengthening of a country's international reputation. In the case of Ukraine, the digitalization of crisis management of remediation processes plays the role of a critically important factor for the efficiency and speed of post-war recovery. In the author's research, the historical and theoretical aspects of the development of the remediation concept are revealed, and a methodological framework for assessing the effectiveness of digital management based on multicriteria models and Monte Carlo simulation is presented. Particular attention is paid to the integration of IoT, AI, UAVs, digital twins, GIS, and blockchain technologies to achieve a comprehensive environmental, social, and economic recovery effect. Recommendations are formulated for the application of digital solutions in the practice of territorial remediation, with an emphasis on the prospects for maximizing Ukraine's potential.

Keywords

Remediation, digitalization, crisis management, recovery, Internet of Things (IoT), artificial intelligence (AI), digital twins, geographic information systems (GIS), unmanned aerial vehicles (UAVs), blockchain, post-war recovery of Ukraine, multi-criteria

decision analysis (MCDA), adaptive management, digital transformation, sustainability, Monte Carlo simulation, resilience.

3.1 Introduction

It should be noted that information systems and technologies at the beginning of the 21st century have become an integral part of all stages of disaster response – from monitoring and forecasting to planning recovery activities, enabling high accuracy in situation assessment, optimization of resource distribution, damage assessment, increased response speed, and coordination among participants involved in all types of operations, including the evacuation of the population, the search for affected individuals, the clearing of debris, and the delivery of critically needed equipment, materials, medicines, and more [1, 2]. Based on the analysis of recent scientific publications, the author has come to the conclusion that remediation, as a complex of various types of activities aimed at restoring territories affected by natural disasters, technological accidents, or military conflicts, is increasingly manifesting its multi-functional significance in modern scientific and practical discourse. Whereas previously remediation was regarded mainly in the context of an environmental process for eliminating different types of soil, water, and air pollution, as well as restoring natural systems, today the focus within this field has significantly expanded, and remediation is now viewed as a powerful instrument for the socio-economic revival of territories. An ecologically restored territory, after the implementation of a complex of remediation measures, becomes a foundation for the return of the population, the resumption of economic activities, the attraction of investments, the creation of new jobs, the development of entrepreneurship, and the revival of the national economy [3]. Thus, remediation acquires the nature of a multiplicative factor, directly influencing the comprehensive restoration of the ecological and socio-economic structures of territorial systems, thereby contributing to the strengthening of the overall resilience of the country. Moreover, the successful implementation of large-scale remediation projects serves as a positive reputational factor for the state, ultimately strengthening its position as, first and foremost, an environmentally responsible participant in the global community.

The relevance of this study is determined by the necessity of a comprehensive understanding of remediation in its new, expanded meaning, especially in the context of Ukraine's post-war recovery, where the consequences of destruction are not only environmental in nature but also deeply socio-economic. According to the 2024 report "Russia-Ukraine War: Environmental Impact", the area of contaminated

land amounts to 20.8 million square meters (of which 79.3 thousand hectares represent burned forests and other vegetation, and 470.0 thousand hectares are subject to inspection and demining, author's note). The estimated damage to land resources is 27.9 billion USD, to water resources – 2.1 billion USD, and to the atmosphere – 17.7 billion USD, with these figures continuing to grow and worsen [4]. In this context, the digitalization of crisis management processes related to remediation opens up new opportunities to enhance the speed, efficiency, and resilience of territorial recovery, making this research topic highly relevant for the contemporary scientific and practical agenda (Fig. 3.1).

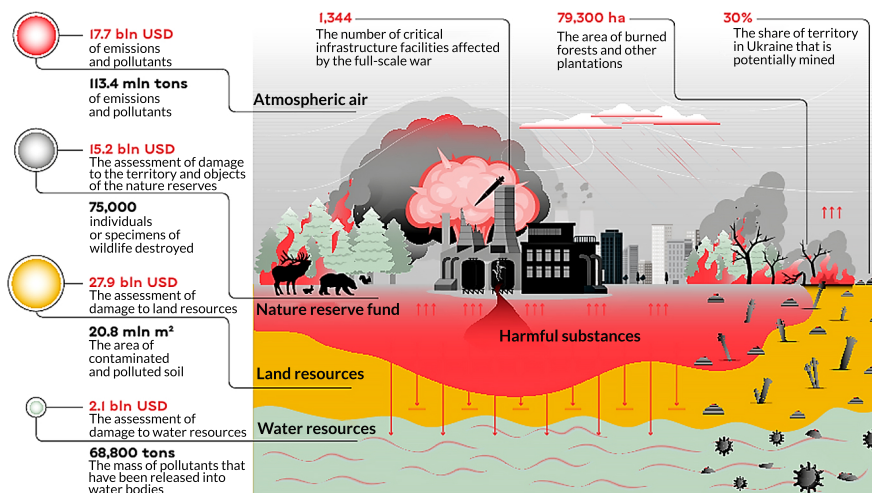


Fig. 3.1 The impact of war in Ukraine as of the end of 2024

Source: [4]

3.2 Historical, theoretical, and methodological aspects of crisis management of remediation

Key Aspects of Historical Development. It should be noted that crisis management as an independent field of governance was formed in the second half of the 20th century, when humanity faced a number of major technological disasters and military conflicts, acutely highlighting the problem of complex response to emergencies and the management of consequences elimination. Initially, efforts were concentrated on the direct liquidation of the consequences of various emergency events and

disasters (namely, locating victims, evacuating the population, clearing debris, extinguishing fires, etc., author's note), whereas environmental remediation (elimination of contaminating substances by various methods, purification of water resources, soil, air, and also waste disposal, author's note) often remained on the periphery of attention and was carried out later [5].

According to the author, traditionally in the practice of crisis management in the second half of the 20th century, the emphasis was mainly placed on organizing emergency response and ensuring the survival of the population, whereas the issues of environmental remediation were not always integrated into the general system of consequence management and often remained under the authority of separate agencies, without sufficient coordination and strategic assessment of long-term damage.

However, the accumulated experience (including, among others, the consequences of the use of defoliants in Vietnam or the environmental damage caused by the Gulf War in 1991) gradually led to the realization that environmental restoration is an integral part of post-crisis recovery (Table 3.1). This was also reflected in the emergence of international and national programs for assessing environmental damage and in remediation projects for affected territories.

Table 3.1 Characteristics of historical events in the context of the expanding functionality of remediation

Historical event	Objectives of remediation	Characteristics of remediation activities	Applied technologies
1	2	3	4
Chernobyl Disaster (1986)	Environmental restoration, minimizing the impact on human health	Isolation of radioactive contamination sources, large-scale decontamination of the environment	Traditional radiation protection methods, basic monitoring systems
Gulf War (1991)	Environmental restoration of marine and terrestrial ecosystems	Cleaning of oil-contaminated water bodies and soils, biodiversity restoration programs	Bioremediation, environmental monitoring, purification technologies
Wars in Yugoslavia (1990s)	Environmental restoration, elimination of consequences of armed conflicts	Demining, soil cleanup, restoration of water supply systems and infrastructure facilities	Demining, mapping of contaminated territories
Fukushima Accident (2011s)	Environmental safety, restoration of normal functioning of infrastructure	Decontamination of territories, restoration of energy and transportation infrastructure	Robotic systems, radiation monitoring, digital twins
Wars in Iraq and Afghanistan (2000s)	Environmental cleanup and restoration of life safety conditions	Removal of explosive objects, bioremediation of contaminated lands	GIS, monitoring drones, early IoT systems

Continuation of Table 3.1

1	2	3	4
Earthquake and Tsunami in Japan (2011)	Infrastructure restoration, ensuring environmental safety	Elimination of hazardous spills, restoration of dams and water supply systems, monitoring of water and soil quality	IoT sensors, early contamination detection systems, robotic cleanup
Wildfires in Australia (2019–2020)	Environmental restoration of ecosystems, prevention of erosion	Reforestation, restoration of water bodies, biodiversity monitoring	GIS, automated monitoring systems, ecosystem restoration technologies
War in Ukraine (since 2022–present)	Environmental, social, and economic restoration of affected territories; strategic strengthening of national resilience	Demining, environmental cleanup, restoration of water resources, revival of agricultural production, reconstruction of social infrastructure, digitalization of recovery monitoring	Integration of IoT, AI, extensive use of UAVs, digital twins, blockchain, intelligent recovery management systems, multi-level GIS platforms

Sources: developed by the author on the basis of data [6, 7]

As can be seen from the data presented in the table, remediation has transformed from an environmentally oriented activity focused on the purification of contaminated environments into a multifunctional recovery instrument that includes social, infrastructural, and economic aspects of rehabilitating affected areas into fully functioning territorial systems. The analysis of emergency events that have occurred since the late 20th and early 21st centuries demonstrates the fact that it can no longer be viewed in isolation from modern digital solutions. Today, its successful implementation is unthinkable without the comprehensive integration of IoT, AI, UAVs, digital twins, GIS, and blockchain technologies, which ensure systematic, coordinated, and resilient restoration of territorial socio-economic systems.

Theoretical and Methodological Foundations. Conceptually, crisis management of remediation represents an interdisciplinary field of research situated at the intersection of emergency management theory, environmental and technical sciences, information technology, and project management. Traditional crisis management models, such as the four-phase model (prevention, preparedness, response, recovery), identify remediation primarily as an element of the final phase – recovery. However, as established by the author, in modern conditions, its effectiveness directly depends on mechanisms embedded in all previous phases, including threat monitoring, rapid contamination diagnostics, risk assessment, and plan adaptation.

In addition, a key role in the theoretical foundation of modern crisis management of remediation is played by the paradigm of sustainable development and the disaster

risk reduction (DRR) concept, which aim to build safe and resilient systems in the long term. In this context, recovery must be seen as a balanced process that integrates environmental, social, economic, and infrastructural aspects – an approach that is particularly vital in post-war territorial transformation.

Additional methodological significance is provided by the theory of catastrophes, which describes the behavior of complex systems under abrupt environmental changes and serves as an important basis for forecasting crisis scenarios, particularly in technologically saturated and environmentally vulnerable zones.

Modern practice convincingly demonstrates that information technologies and digital platforms have become an integral part of the theoretical and practical toolkit for remediation. It is necessary to consider the advances of computer science, cyber-physical systems, artificial intelligence and machine learning (AI/ML), the Internet of Things (IoT), and digital modeling (digital twins), all of which establish a new level of spatiotemporal control over crisis and post-crisis processes.

Furthermore, it would be methodologically inappropriate to ignore project analysis, particularly in the context of the program-targeted approach, which is widely applied in international practice.

According to the author, the following foundational approaches serve as the methodological basis:

- the systems approach – as the foundation for building interconnections between natural, technological, and social components of the territory;
- the integrated approach – for evaluating and coordinating all elements of recovery;
- the situational approach – for adapting management decisions depending on changing conditions and uncertainty factors;
- the cybernetic approach – for analyzing feedback cycles in digital monitoring and remediation control systems.

Thus, the theoretical and methodological basis for crisis management of remediation in the 21st century is a hybrid interdisciplinary model, grounded in the principles of sustainability, digitalization, controllability, predictability, and project implementability [8].

It is also necessary to emphasize that the complexity of modern remediation tasks has necessitated the inclusion of decision-support approaches into the theoretical and methodological framework – especially under conditions of multicriteriality, uncertainty, and limited resources. A significant contribution to the scientific foundation has been the spread of multi-criteria decision analysis (MCDA) methods, which allow for structured choice among alternatives based on a set of environmental, technical, economic, and social criteria. This is particularly relevant for remediation, where one must not only achieve maximum decontamination, but also meet deadlines, remain within budget, minimize risks for implementation teams, and account for the interests of all stakeholders.

In addition to MCDA, adaptive management is actively applied – a concept originally proposed in the 1970s in ecosystem management and now reinterpreted for long-term environmental and infrastructural rehabilitation processes.

Simultaneously, the past decades have witnessed intensive development of digital theories and models of crisis management, which, in the author's view, have fundamentally transformed the methodology of remediation management itself. Theoretically, this is reflected in the concept of Digital Crisis Management, which entails the integration of digital solutions at all stages of the crisis cycle – from monitoring and forecasting to recovery and impact assessment. The first signs of digitalization emerged at the end of the 20th century with the development of geographic information systems (GIS) and satellite imagery, making it possible to map contaminated territories and model the spread of pollutants (Fig. 3.2).






Theoretical and Methodological Foundations of Remediation			
Characteristic	Traditional Crisis Management	Modern Crisis Management	Digital Crisis Management
 Focus	Recovery phase element	All phases, sustainable development	All stages of crisis cycle
 Key Theories	Four-phase model	Sustainable development, DRR, catastrophe theory	Digital Crisis Management
 Methodological Approaches	Project analysis	Systems, integrated, situational, cybernetic	Optimization, modeling, data governance, adaptive
 Key Technologies	None explicitly mentioned	Information technologies, digital platforms	GIS, satellite imagery
 Decision Support	None explicitly mentioned	Multi-criteria decision analysis (MCDA), adaptive management	Digital theories and models

Fig. 3.2 The theoretical and methodological basis for the digitalization of crisis remediation management
Sources: developed by the author

In summary, it can be concluded that the theoretical and methodological foundation of digitalized crisis management of remediation now includes not only classical managerial concepts but also modern hybrid approaches, based on optimization algorithms, modeling, digital data governance, and adaptive strategies. All of the above contributes to the formation of a new paradigm of sustainable and technologically grounded territorial recovery, which demands in-depth scientific evaluation of the effectiveness of applied digital solutions and forecasting of their further efficient development [9].

3.3 Methodical decomposition of the study

To objectively assess the effectiveness of remediation processes in the context of the impact of digital technologies, the author proposes a methodological framework. It is based on a hybrid multi-criteria model, utilizes Monte Carlo simulation to account for uncertainties, and implements the principles of adaptive management. The main components of this methodology are presented below.

Multi-Criteria Model of Remediation Effectiveness. As a starting point, the need to account for several key aspects of the effectiveness of remediation management within a specific territorial system is emphasized: focus, locus, resources, and time. An integrated effectiveness indicator E is proposed as a generalized index reflecting the success of all remediation activities, aggregating the aforementioned aspects while considering their relative importance.

The formal structure of the index can be represented as follows

$$E = \sum_{i=1}^n (\alpha_i F_i^\lambda + \beta_i L_i^\mu + \gamma_i R_i^\nu + \delta_i T_i^\xi) \cdot \omega_i \cdot D, \quad (3.1)$$

where F – reflects the degree to which resource allocation aligns with recovery priorities ("focus"); L – denotes the effectiveness of the decision-making system and responsibility distribution ("locus"); R – reflects the efficiency of resource utilization (financial, human, material, etc.); T – represents temporal indicators (including the speed of implementing works related to post-conflict damage and contamination remediation).

The coefficients $\alpha, \beta, \gamma, \delta$ are weighting parameters that reflect the relative importance of each structural component in the overall effectiveness, while λ, μ, ν, ξ characterize the degree of influence that changes in the corresponding factor have on the final result.

The multiplier ω represents the composite project condition coefficient, accounting for landscape complexity, the scale and type of contamination, etc., and allows the normalization of the E index across different cases.

Finally, special attention is given to the D coefficient – the Digital Factor, which reflects the level of integration of digital technologies in the remediation project of the specifically analyzed territory. In other words, D indicates the intensity with which Digital Crisis Management (DCM) tools are used in the planning and implementation of remediation activities.

Digitalization Coefficient D . To mathematically formalize the impact of various digital technologies on the effectiveness of remediation activities, the author introduces the coefficient D , which is included multiplicatively in the formula for E , thereby increasing its value when various information-based solutions are actively applied within DCM.

The value of D is calculated based on which specific digital technologies are utilized and the extent of their practical contribution. Formally, it can be represented as

$$D=1+\sum_{j=1}^m\left(\omega_j T_j \cdot N\left(\mu_j, \sigma_j\right)\right), \quad (3.2)$$

where m – represents the number of available digital technologies used in the remediation of a specific territory; T_j – a binary indicator of the use of the j -th digital technology (0 – not used, 1 – used); ω_j – reflects the weight or significance of the technology for the specific remediation project; $N(\mu_j, \sigma_j)$ – the distribution function of the technology's effect, modeled as a normal distribution with expected influence μ_j and uncertainty σ_j (author's note).

Thus, if a particular technology is not applied, its contribution to D equals zero. However, if the digital technology is in use, its contribution is treated as a random variable reflecting the variability of its effect. The baseline value $D = 1$ corresponds to the absence of digital tools, while $D > 1$ indicates a positive digitalization impact on the overall effectiveness index E .

Accounting for Uncertainties Using the Monte Carlo Method. The remediation process takes place under conditions of significant uncertainty: in most cases, the outcomes may depend on weather conditions, the risk of technical failures, variations in the level and nature of contamination, as well as numerous other random factors.

To ensure the reliability of the effectiveness assessment, the author applied the Monte Carlo method in the proposed methodology. This method enables scenario analysis and allows the determination of the range of possible values for key indicators.

The Monte Carlo method, originally developed by J. von Neumann and S. Ulam in the 1940s, is based on repeatedly performing calculations with random variations in the input parameters [10].

In the context of this study, multiple iterations of the model produced a distribution of possible values of E , from which both the average expected remediation

effectiveness and confidence intervals can be derived. According to the author, this contributes to more substantiated managerial decision-making – rather than relying on a single deterministic estimate, a range is provided that takes into account specific conditions and overall risks [10, 11].

Thus, the use of the Monte Carlo method enables the most objective modeling of the remediation process under uncertainty and allows for analysis of the influence of various factors on the overall effectiveness of activities. This is critically important for reliable planning in crisis conditions (particularly when operating under time constraints and resource scarcity).

Adaptive Management and Dynamic Adjustment of Parameters. Another innovation in the effectiveness metric proposed by the author is the introduction of a feedback mechanism, which enables the adaptive adjustment of model parameters as new data becomes available regarding the progress of recovery activities on objects and territories.

Since the remediation process unfolds within a specific time frame, actual indicators – such as the achieved level of decontamination (F_{real}), the pace of implementation (T_{real}), the volume of resources consumed (R_{real}), etc. – may deviate from initially planned values ($F_{expected}$, $T_{expected}$, $R_{expected}$, and so on).

The methodology proposed by the author provides for the periodic recalculation of the coefficients λ , μ , ν , ξ , which are the very parameters responsible for the model's sensitivity to each structural component of effectiveness. This recalculation is carried out by computing the ratio of actual to expected values:

$$\lambda_{new} = \lambda_{old} \cdot F_{real} / F_{expected}; \quad (3.3)$$

$$\mu_{new} = \mu_{old} \cdot L_{real} / L_{expected}; \quad (3.4)$$

$$\nu_{new} = \nu_{old} \cdot R_{real} / R_{expected}; \quad (3.5)$$

$$\xi_{new} = \xi_{old} \cdot T_{real} / T_{expected}. \quad (3.6)$$

Such proportional adjustment means that if a certain component is being implemented with more difficulty than expected (for example, if the actual efficiency of resource utilization R_{real} turned out to be lower than initially planned $R_{expected}$), then the significance of this structural component (ν) automatically increases. This signals to the management personnel responsible for the remediation outcomes that greater attention must be paid to the rational use of this type of resource. Thanks to this adaptive mechanism, the remediation management model becomes more viable and

capable of adjusting to current conditions and constraints. This corresponds to the concept of Adaptive Control – dynamic management in which decisions are made at each moment based on the current situation rather than strictly following the initial plan. As envisioned by the author, this approach makes it possible to achieve a higher level of resilience of the remediation process to external changes, since the model itself will indicate where to redirect efforts and resources if the implementation of the project deviates from the original plan. Taken together, the elements described above – the multi-criteria effectiveness index with the digitalization coefficient D , scenario analysis implemented via the Monte Carlo method, and the parameter adaptation mechanism – form a comprehensive methodological construct. This can be characterized as a digital remediation management support system. In essence, the author proposes a prototype of a Digital Crisis Management System (DCMS) for post-crisis recovery, which integrates traditional methods (expert evaluation, planning) with digital technologies for modeling and analysis. The proposed approach not only allows for a one-time assessment of the effectiveness of a remediation project for a specific territory but also ensures continuous support for the post-crisis recovery process by providing management personnel at all levels of hierarchy with up-to-date information for timely response and decision-making at every stage [12].

3.4 Assessment of the role and significance of digital technologies in the remediation of affected territories

As previously noted, digital technologies exert a comprehensive influence on remediation processes – from the stages of monitoring and damage assessment to the planning and direct implementation of recovery efforts. The following section presents an analysis of key technologies (unmanned aerial vehicles, artificial intelligence, digital twins, IoT, Big Data, blockchain, etc.), evaluations of their practical application in remediation, as well as the effects achieved and the potential advantages of integrating these solutions.

Unmanned Aerial Vehicles (UAVs) in Remediation. One of the most prominent advancements in recent years has been the widespread use of unmanned aerial vehicles (drones) for environmental monitoring and restoration tasks. Drones possess a number of unique advantages, namely: they are highly mobile, capable of reaching hard-to-access or hazardous areas, rapidly collecting high-resolution data (including photo and video imagery, thermal imaging, LIDAR, etc., *author's note*), and even performing active operations (such as spraying reagents, delivering small cargo, conducting remote sensing, and more, *author's note*).

In the context of remediation, UAVs function as the "eyes and hands" in the localization zone of the crisis event. The practice of using drones in post-conflict and post-disaster remediation is already actively taking shape. For example, in Ukraine, a project is underway for the decontamination of agricultural land, in which specially trained experts use drones to map contaminated areas and collect soil samples [13]. Drones make it possible to promptly identify areas contaminated by shell fragments and hazardous substances, significantly accelerating the initial stage of remediation. In addition, they can be used to deliver necessary reagents and even equipment to regions that are difficult to access by ground vehicles (for example, in swamped areas or zones with destroyed infrastructure following an environmental disaster, such as after the destruction of the Kakhovka Hydroelectric Power Plant dam) [14].

Research shows that the effectiveness of UAV application largely depends on the specifics of the territory and the tasks at hand. Several main types of drones are distinguished by their functions: *Reconnaissance (mapping) drones* – used for aerial photography and subsequent mapping of damage and contamination; *Analytical drones* – equipped with special sensors for analyzing soil, water, air, and radiation levels; *Logistical (delivery) drones* – intended for transporting material resources (usually compact items, including medicines, tools, reagents, soil samples, etc., author's note); *Bioremediation drones (sprayers)* – designed to apply reagents, phytoremediation seeds, bacteria, and similar agents to designated areas. Each type of drone has its own optimal areas of application accordingly.

Artificial Intelligence and Machine Learning. As practice shows, artificial intelligence (AI) and its applied methods – machine learning (ML), neural networks, and intelligent data analysis – are becoming powerful tools for decision support in crisis management, including post-conflict remediation. AI is capable of solving tasks traditionally requiring expert involvement while automating and accelerating the process. In the context of crisis remediation management, AI developments are applied in several key areas, including:

1. *Analysis of large volumes of heterogeneous data.* Environmental assessments following a crisis generate enormous amounts of diverse data, including satellite imagery, drone-based aerial photography, IoT sensor readings, laboratory results of water and soil samples, field reports from emergency response sites, and more. Manual processing of such information is virtually impossible. In this regard, machine learning algorithms make it possible to detect hidden patterns and anomalies within the collected datasets. For example, neural networks can automatically classify types of landscape or structural damage based on imagery, and identify contamination levels through indirect indicators (such as vegetation color, processed from infrared imaging data, etc.). This significantly accelerates the creation of contamination maps and

damage assessments, while also optimizing the range of management decisions aimed at mitigating the consequences [15].

2. Forecasting and Modeling. It is especially important to emphasize the fact that AI models are successfully used to forecast the occurrence of emergency events themselves (for example, the globally renowned Copernicus platform), as well as to predict their consequences, including the spread of pollutants. Models trained on historical data can forecast the development of situations, complementing physical models [16].

3. Decision Optimization. The author's research places particular emphasis on the capabilities of AI-based optimization. Specifically, the focus is on the potential application of bio-inspired algorithms, which help solve remediation tasks under constrained conditions – for instance, selecting the most effective sequence for cleaning multiple sites, optimally allocating resources across various locations, or choosing the most efficient logistics route for delivering necessary materials.

Classical optimization algorithms (such as the Artificial Bee Colony algorithm, Ant Colony Optimization, Genetic Algorithms, Particle Swarm Optimization, etc.), when combined with simulation modeling, can propose an action plan that delivers maximum impact with minimum cost [17].

4. Robotics and Automation. It is also important to emphasize the role of AI, which provides the "intelligent core" of autonomous systems used in crisis management, including those applied in remediation operations. This primarily includes drone autopilots, image recognition from onboard cameras, and the action algorithms of demining robots used for neutralizing munitions, etc.

It should be noted that the more autonomous such systems are in performing dangerous operations, the lower the risk to human life and health, and the higher the speed of completed tasks. There are already examples where an onboard neural network on a drone recognizes a chemical barrel or a landmine in real-time video footage and immediately marks and transmits coordinates to a demining team [18].

5. Digital Twins + Artificial Intelligence. Particular attention should be paid to the role of AI in combination with digital twins and IoT: by receiving data streams from sensors, AI can diagnose deviations in real time (for example, a sharp increase in toxin concentration from a sensor may trigger a set of proposed actions, author's note), or even initiate an automatic decontamination response.

This approach brings closer to automated adaptive management, where the system responds independently to changes in the environment with minimal human intervention. This can be described as AI functioning as the "brain" of the digital remediation system for affected territories, where a designated official retains the authority to make managerial decisions. When applied correctly, this significantly enhances both the speed and validity of such decisions. Nonetheless, limitations must

also be considered: AI models require large volumes of high-quality training data, may suffer from lack of transparency (the "black box" problem of neural network decision explainability), and do not guarantee 100% accuracy. Therefore, the author considers a hybrid approach to be optimal – where AI assists humans by handling routine and computationally intensive tasks, while key decisions are made by experts using forecast data provided by AI. In the future, as successful use cases of AI in remediation accumulate, trust in these technologies will continue to grow, and in the author's opinion, they will become a standard component of crisis management [19].

GIS and Cartography. It is important to emphasize that, in practice, the creation of a digital twin begins with a high-quality cartographic foundation. Modern remote sensing tools (such as ultra-high-resolution satellites, drones with scanners, etc., author's note) play a vital role in this process, ultimately enabling the creation of detailed 3D terrain models. In this context, GIS platforms are used to further integrate various data sources. In remediation processes, GIS is often employed to assess conditions in a specific area in order to analyze the level of different risks. For example, risk maps are created to illustrate the degree of hazard in various locations (such as heatmaps of groundwater contamination spread or interactive minefield maps, author's note) [20, 21].

The above-mentioned remediation processes demonstrate a strong interconnection with other digital technologies, as they are "fed" by IoT data, utilize AI for rapid analysis and forecasting, are visualized through GIS, and the modeling results are used to control actual drones and machinery. This is the quintessence of digitalization – where the virtual model continuously interacts with the real world, enhancing decision-making and actual outcomes on the ground.

Internet of Things (IoT) and Sensor Networks. The author has conducted an in-depth analysis of the role and significance of the Internet of Things (IoT) in the remediation process. Essentially, it is a network of physically distributed sensors and devices interconnected with data processing centers via the Internet or other communication channels for the purpose of achieving set objectives.

In the field of remediation, IoT functions as the "nervous system" of the territory, as numerous heterogeneous sensors installed throughout the area continuously monitor environmental parameters and transmit data to the control center. Installed sensors allow for monitoring of: Water quality (including the presence of heavy metals, radioactive substances, phosphorus and nitrogen compounds, chlorine-, bromine- and fluorine-containing components, various pathogenic microorganisms, etc., author's note); Soil parameters (including mercury, lead, cadmium, arsenic, zinc, copper, and others, author's note); Air quality (such as the concentration of harmful gases, particulates, etc., author's note); Radiation levels, temperature, and

more. Additionally, IoT includes tracking the movement of equipment and personnel (GPS trackers), monitoring equipment status, weather stations, and even wearable sensors on personnel (to monitor the health of individuals directly involved in emergency response activities).

Big Data and Cloud Technologies. The very concept of "Big Data" is closely linked to the digitalization of crisis management related to the elimination of the consequences of emergencies and remediation, as all the aforementioned sources (drones, sensors, models, social networks, etc.) generate colossal volumes of information. The ability to collect, store, process, and analyze these data becomes critically important for achieving the set goals in the shortest possible time and with maximum possible efficiency. Cloud technologies in this regard provide virtually unlimited possibilities for storing large arrays of various types of information and accessing them from almost anywhere in the world. In the context of remediation, this means that all data related to the implementation of Ukraine's post-war recovery strategy – from high-resolution satellite images (weighing gigabytes) to the results of millions of simulations – can be stored centrally but accessed in a distributed manner.

A participant (for example, a financial donor or investor, *author's note*) can, in real time and from anywhere in the world, view the necessary project data related to remediation efforts in Ukraine without having to download all the information onto their local computer, working instead through a cloud service. This greatly facilitates collaboration among international teams, which are often involved in crisis management and disaster recovery projects. Big Data analysis involves the use of specialized methods and platforms (Hadoop, Spark, NoSQL databases, etc.) optimized for handling volumes that exceed the capabilities of conventional spreadsheets.

It should be noted that Big Data may also include social data – feedback from local residents in areas where remediation activities are being carried out, media reports, and reports from various organizations and agencies. Analyzing such data makes it possible to monitor public perception of the recovery process, respond promptly, identify bottlenecks, and assess indirect effects (for example, how quickly residents return to settlements restored after hostilities – this is also an indicator of success). Combining such social data with environmental indicators provides a more holistic picture of the recovery of affected territories.

Big Data is often accompanied by visualization tools – dashboards and interactive graphs – which help transform "raw" numbers into understandable formats for all participants in the recovery process, aimed at making more effective decisions.

Blockchain and Ensuring Data Transparency. It should be noted that although blockchain originally emerged in the context of cryptocurrency development, its unique fundamental properties – namely, decentralization, immutability of records, and

transparency – have attracted attention across a wide range of industries, including post-crisis recovery management.

According to the author's vision, in the field of remediation, blockchain can play a supporting but important role: it can ensure trust between project participants and supervisory authorities, eliminate data falsification concerning the progress and results of post-conflict destruction and contamination elimination efforts, and overall enhance the level of transparency and accountability. Smart contracts – another facet of blockchain technology – can, in the author's opinion, be applied to automate certain contractual aspects of remediation activities [22, 23].

Of course, the successful implementation of blockchain and smart contracts depends on the digital maturity of participants and the proper functioning of the relevant infrastructure. In the context of the post-war situation in Ukraine, where infrastructure has been partially destroyed, the author believes that such digital solutions can be introduced gradually, beginning with pilot projects in relatively stable regions. Nevertheless, it should be especially emphasized that international organizations financially supporting Ukraine's post-war recovery and revival are increasingly interested in the implementation of digital transparency tools to ensure that the resources they provide are used strictly for their intended purposes [24].

In conclusion, in order to confirm the relevance and significance of the research problem raised, it is appropriate to present a generalized analytical snapshot of the overall dynamics of the implementation of key digital technologies in the field of remediation and crisis management during the period from 2020 to 2025 (Table 3.2).

Table 3.2 Dynamics of the implementation of key digital technologies in the field of remediation and crisis management in the period from 2020 to 2025

Digital Technology	Growth dynamics and scaling forecast	Main areas of application
1	2	3
Internet of Things (IoT)	The number of connected IoT devices increased from 16.6 billion in 2023 to 18.8 billion in 2024; expected to reach 27 billion by 2025	Environmental monitoring, infrastructure management, real-time data collection
Artificial Intelligence (AI)	The global AI market reached 298.25 billion USD in 2024 and is projected to grow to 420.47 billion USD by 2025	Data analysis, forecasting, decision-making support
Unmanned Aerial Vehicles (UAVs)	The installed base of commercial drones reached 2.8 million units in 2024; expected to grow to 4.5 million by 2029	Aerial photography, material delivery, monitoring of hard-to-reach areas
Digital Twins	The global digital twin market was valued at 24.97 billion USD in 2024, with a projected CAGR of 34.2% until 2030	Process modeling, forecasting, operational optimization

Continuation of Table 3.2

1	2	3
Geographic Information Systems (GIS)	The GIS market is expected to reach 94.59 billion USD by 2025 with a CAGR of 6.38% until 2030	Mapping, spatial data analysis, route planning
Big Data	The global Big Data market is projected to reach 348.21 billion USD by 2025; growth to 924.39 billion USD is expected by 2032	Large-scale data analysis, pattern recognition, decision-making support
Blockchain	The global blockchain technology market grew from 4.19 billion USD in 2020 to 26.91 billion USD in 2024; forecast to reach 248.9 billion USD by 2029	Transparency assurance, data protection, supply chain management

Sources: developed by the author on the basis of data [22, 23, 25–29]

The data presented above clearly demonstrate the rapid development and integration of digital technologies, including in crisis and emergency management processes such as remediation. The forecast indicators underscore their importance for enhancing the efficiency of response and management, as well as for achieving resilience in the face of growing modern challenges.

3.5 Results of the testing of the methodical model for assessing the role and significance of digital technologies in remediation efficiency

The applied approaches to Digital Crisis Management (DCM) for territories affected by armed conflicts and emergency events demonstrate the urgent need to transition from traditional methods to digital hybrid crisis management systems. In this study, a comprehensive analysis of the role and significance of individual technologies was previously presented. However, recent scientific publications confirm that the isolated application of digital technologies shows a certain limitation in their effectiveness and does not provide the required level of dynamic adaptability in management.

Below are the results of the conducted analysis, which demonstrate the leading and unconditional significance of artificial intelligence (AI), as well as all types of drones (UAVs), GIS, Big Data, and machine learning (ML) in contributing to remediation efficiency (Fig. 3.3). During the testing of the previously proposed model for assessing the contribution of various digital technologies to the overall digitalization index of remediation process management – the D coefficient – the author relied on the concept of multi-criteria analysis and adaptive management, integrating expert evaluations, probabilistic modeling, and elements of digital monitoring.

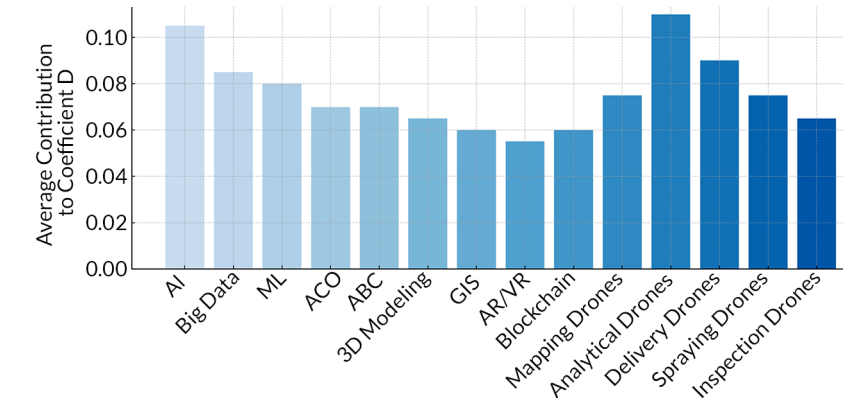


Fig. 3.3 Contribution characteristics of each technology to the overall remediation efficiency
Sources: developed by the author

In the course of modeling remediation efficiency, the author conducted a simulation of 10,000 trials aimed at assessing the distribution of the D coefficient, which reflects the integral efficiency of remediation. The use of the Monte Carlo method made it possible to account for the variability of parameters such as funding levels, weather conditions, technology failure risks, and regulatory barriers [11]. As a result of the calculations, it was found that an increase in the implementation of technologies (including UAVs) leads to a rise in the D coefficient; however, its variability also correlates with external constraints.

The author also carried out a more detailed analysis of the contribution of individual technologies to the calculation of the D coefficient. The results showed that AI ranks first in terms of impact (10.76%), followed by Big Data (7.21%), Machine Learning (8.67%), and GIS (6.3%) in fourth place. This distribution is explained by the role each of the analyzed DM (Digital Management) technologies plays in collecting primary data, continuous processing, contamination analysis, identification of optimal remediation scenarios, and route optimization. Among UAVs, the greatest contribution to the D coefficient is made by mapping drones (8.9%), followed by delivery drones (6.5%), which confirms their critically important role in monitoring and resource delivery. The least significant among all analyzed DM technologies was blockchain (4.2%), which is due to its predominantly auxiliary function in the remediation process.

Below are the results of the remediation efficiency model simulation presented as a radar chart, visualizing the potential of each DM technology across key characteristics: speed, cost, accuracy, adaptability, and transparency (Fig. 3.4).

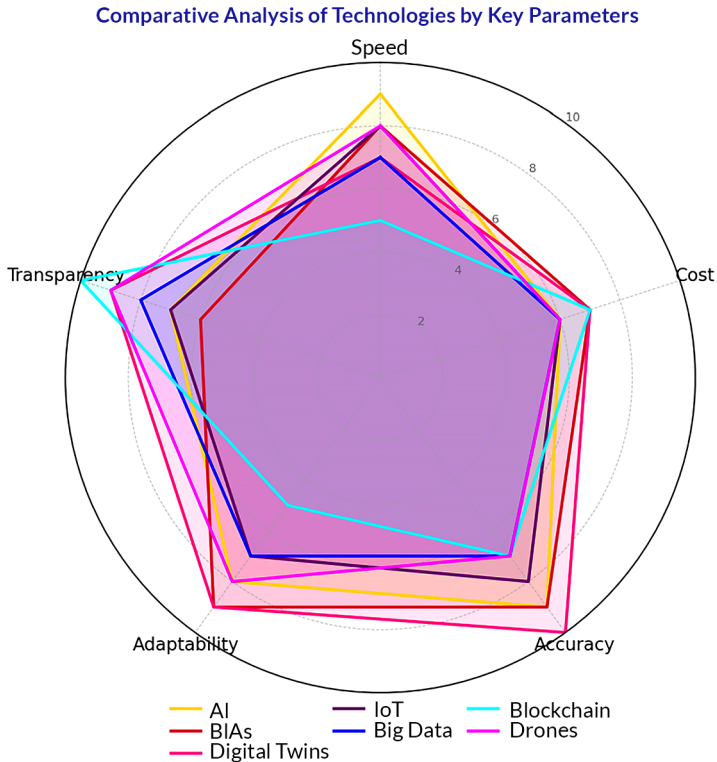


Fig. 3.4 Visual analysis of DM technologies used in remediation across key parameters
Sources: developed by the author

The presented chart clearly demonstrates both the strengths and weaknesses of each analyzed DM technology, thereby helping to identify optimal combinations for their implementation in remediation processes.

Summarizing the obtained results of modeling and analysis, it can be concluded that to ensure high recovery efficiency under conditions of time and resource constraints, the use of a single digital technology will not be sufficient. A synergistic integration of artificial intelligence, various types of UAVs, GIS, Big Data, and machine learning provides the most significant positive effect, substantially enhancing the speed, accuracy, adaptability, and transparency of post-crisis recovery processes.

The conclusions and generalizations reached by the author of this monographic study confirm the urgent need for comprehensive digitalization of crisis management

systems, where the optimal combination of digital technologies will enable the maximization of all their advantages within a unified integrated digital framework.

3.6 Conclusion

In the 21st century, remediation has transformed into something more than just the cleaning of contaminated areas and the restoration of ecosystems. Today, it plays the role of a crucial mechanism for the strategic revival of territories affected by emergency events: the restoration of the ecological environment triggers the return of people, stimulates economic development, improves the quality of life, and strengthens the international image of the country. It is remediation that can launch a multiplicative effect, which has strategic significance, including for Ukraine. The main conclusions of the study indicate that digitalization brings qualitatively new opportunities to crisis management of remediation processes and can significantly enhance their efficiency.

The conducted study has applied value through the developed methodology for assessing the effectiveness of remediation using digital technologies. The integrated model proposed by the author, which includes the calculation of the digitalization coefficient D and an adaptive mechanism for the dynamic adjustment of parameters, will enable an objective, multi-criteria assessment of the success of remediation activities under conditions of uncertainty and resource constraints. This makes the methodology particularly relevant and important for use in post-crisis scenarios where prompt and effective management decisions are required, based on the comprehensive consideration of ecological, social, and economic factors.

The developed methodology can be especially effective in the context of designing the post-war recovery program for Ukraine, allowing for the transparency and optimization of resource allocation. Thanks to the flexibility of its architecture, the methodology can be adapted to different types of emergency situations – from the consequences of armed conflicts to technological accidents and natural disasters. Thus, the model presented in the study can become an organic structural element of a modern strategy for the sustainable development of post-crisis territories.

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CHAPTER 4

Implementation of blockchain technologies and smart contracts as a driver of international investment activity in the post-war recovery of Ukraine

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Abstract

Blockchain and smart contract technologies are increasingly being considered as catalysts for boosting international investment activity. This study thoroughly explores how the implementation of blockchain and smart contracts can ensure transparency, trust, and efficiency in the process of restoring territories in Ukraine affected by military activities, thereby attracting foreign capital. The authors of the monograph present the genesis and potential of blockchain, describe a methodological model that includes a semantic analysis of key concepts (such as "remediation" and "revitalization"), and provide an analytical assessment of the introduction of blockchain to stimulate foreign investment in Ukraine's post-war recovery. The authors present a project model of a blockchain system developed to support transparency within a specific settlement's post-war remediation and revitalization project, with an emphasis on anti-corruption control and digital transformation of recovery efforts. Drawing on Ukrainian and international cases – from fundraising via cryptocurrencies during the war to blockchain-based land registries and procurement systems – the authors emphasize that the integration of blockchain and smart contracts can eliminate the human factor in record-keeping, ensure open access to information, and automate the execution of agreements. This, in turn, can increase the level of investor trust and open new opportunities for financing such projects (including through asset tokenization and smart contract-based funds). Special attention is paid to ensuring accountability in the use of resources for territorial recovery and to the role of blockchain in creating a transparent, corruption-resistant environment.

Keywords

Blockchain, smart contracts, international investments, post-war recovery, re-mediation, revitalization, digital transformation.

4.1 Introduction

As a result of the full-scale war, a significant part of Ukraine has been left in a state of destruction, requiring unprecedented volumes of investment for recovery [1]. According to estimates by the World Bank, reconstruction needs amount to about 411 billion USD, which significantly exceeds the capabilities of the state itself. Such a large-scale post-war recovery is impossible without active involvement of international investments, donor assistance, and private foreign capital. However, the key condition for the inflow of funds from abroad is trust – the confidence of investors in the transparency and efficiency of resource utilization. Historically, Ukraine has had a high level of perceived corruption and non-transparency, which could discourage foreign partners. Accordingly, ensuring transparency, accountability, and anti-corruption control in recovery projects becomes not merely a technical task but a fundamental requirement for the success of the country's post-war development.

In this context, blockchain technologies and smart contracts appear as promising tools capable of radically enhancing trust in the investment process. Blockchain (a distributed ledger) allows recording transactions immutably without intermediaries, ensuring the invariability and permanence of records [2]. All participants of the system can access a single trustworthy version of the data, eliminating information asymmetries and possibilities for hidden manipulations. Smart contracts – programmable "intelligent" agreements that automatically execute when predefined conditions are met – make it possible to guarantee the targeted use of funds: for example, embedding in the code conditions under which payment to a contractor will occur only after confirmation of the completion of a specific work stage. Thus, the combination of blockchain and smart contracts can eliminate the human factor in the allocation of funds, reduce the risk of misappropriation to zero, and ensure "zero corruption" through process automation and transparency [3, 4].

Ukraine already has a strong foundation for implementing such innovations. On one hand, the country ranks among the world leaders in the adoption of cryptocurrencies and blockchain by the population – in 2022, Ukraine ranked 3rd in the Global Crypto Adoption Index [5].

According to various estimates, between 5 and 6 million Ukrainians use cryptocurrencies, driven by a high level of digitalization, the need for financial flexibility, and

wartime experience [6]. On the other hand, the government demonstrated openness to blockchain initiatives both before and during the war: as early as 2017, Ukraine concluded the world's largest agreement at that time on blockchain implementation in public administration (a partnership with Bitfury) to transfer state registries to a distributed ledger to enhance transparency [7].

In 2022, Ukraine joined the European Blockchain Partnership (EBP) as an observer, becoming the second non-EU country (after Norway) to participate in the pan-European project for using blockchain in cross-border public services [8, 9]. This indicates a strategic course towards the integration of blockchain solutions into the public sector and synergy with European digital initiatives. Moreover, during the war, the government and volunteer foundations effectively utilized virtual assets: within the first months of the invasion, more than 50 million USD in cryptocurrency donations were raised to support Ukraine, and the Ministry of Digital Transformation officially launched crypto-funds to assist the military and humanitarian needs. The successes of rapid and targeted fundraising through blockchain during active hostilities proved the effectiveness of this technology in establishing donor trust, mobilizing resources quickly, and ensuring their transparent distribution [10].

Thus, there is an urgent need for a comprehensive study on how the implementation of blockchain technologies and smart contracts can become a driver of international investment activity in Ukraine during the post-war recovery phase.

This research aims to identify the potential of blockchain in ensuring investment inflows through enhanced transparency and trust, analyze relevant global and Ukrainian experiences, and propose a conceptual model of a blockchain-based system for managing recovery projects, including the remediation (environmental cleanup and restoration) and revitalization (economic and social revival) of affected territories. The focus is on mechanisms through which blockchain can ensure the targeted and efficient use of reconstruction funds, improve the investment climate, and serve as a foundation for an anti-corruption ecosystem in the new Ukraine.

4.2 Genesis and analysis of blockchain potential

The Emergence and Evolution of Blockchain Technologies. It should be noted that the concept of blockchain originated in 2008–2009 with the appearance of Bitcoin – the first decentralized cryptocurrency, which was built upon distributed ledger technology. At its core was the idea proposed by Satoshi Nakamoto that participants in the network could independently verify and store transactions in a chain of blocks, thereby eliminating the need for a trusted central authority [11].

The first generation of blockchain (Bitcoin) was intended for peer-to-peer transfers of value. However, in 2015, the development of blockchain entered a new phase with the launch of the Ethereum platform, which introduced smart contracts – programmable scripts executed on the blockchain. This marked the transition to the second generation of blockchain, significantly expanding the range of its applications beyond cryptocurrencies.

It should be noted that smart contracts have enabled the creation of decentralized applications (dApps) across a wide range of domains – from finance (namely, decentralized finance, DeFi), supply chain management in transportation and logistics, to the administration of state registries. In recent years, we have witnessed the emergence of "Blockchain 3.0", focused on scalability, speed, and integration with the real sector (referring to the emergence of networks such as Polkadot, Cardano, as well as enterprise blockchain systems) (Fig. 4.1).

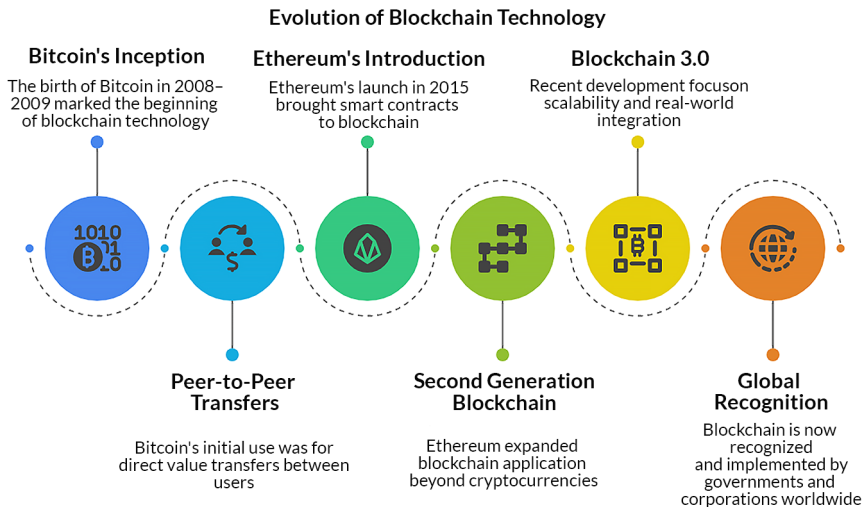


Fig. 4.1 Characterizing key milestones in the evolution of blockchain

Thus, in a remarkably short period of time, blockchain has evolved from a niche tool for crypto enthusiasts into a widely recognized innovation adopted by governments and corporations around the world.

Key Advantages and Capabilities of Blockchain. The core potential of blockchain technology is concentrated in its consistency, namely, in its decentralized nature, which ensures new levels of trust and absolute transparency. The morphogenesis

of blockchain is represented as a distributed ledger collectively maintained by all nodes in the network; each record (transaction) is encrypted and grouped into a block, which is directly linked to the previous block through a cryptographic hash, thereby forming a continuous chain. Precisely because of this, data recorded on the blockchain is virtually impossible to falsify or, for example, modify retroactively, since achieving this would require simultaneously compromising the majority of network nodes. Undoubtedly, any unauthorized attempt to alter the data would be immediately visible. Thus, blockchain creates immutable and permanent records of transactions in real time, without the need for a third party for verification purposes [2].

It is precisely this consistent property of blockchain technology that makes it possible to radically increase the reliability of record-keeping and significantly reduce operational risks. Based on this, the key and unique attributes of blockchain are transparency and verifiability: all participants (in the case of public blockchains, this can be anyone) can view the complete history of all operations. For instance, in such public networks as Ethereum or Bitcoin, absolutely all transactions are open and available for audit (however, without disclosing the personal data of address owners). In contrast to private or enterprise blockchains, where access is restricted, participants in a public blockchain network have a synchronized copy of the ledger, which eliminates the very possibility of discrepancies. Security is ensured through a combination of cryptographic methods (in this case, referring to electronic signatures and hashing) and distributed consensus (namely, the mechanism by which nodes "agree" to add new blocks – such as Proof of Work, Proof of Stake, etc.). As a result, a blockchain system is completely resistant to failures and malicious attacks, since the absence of a single point of failure and the presence of multiple confirmations for each transaction provide a much higher level of data protection than traditional centralized databases [12].

Smart Contracts and Process Automation. Smart contracts expand the capabilities of blockchain by enabling not only the storage of data, but also the execution of embedded logic. Essentially, a smart contract is a piece of program code deployed on the blockchain that automatically executes prescribed actions once the conditions explicitly specified within the contract are met. In other words, it is a digital analogue of a traditional agreement, endowed with self-executing provisions. The built-in "if-then" mechanisms allow for the implementation of tokenized targeted financing and the guaranteed fulfillment of the obligations outlined in the contract. At the same time, neither party can unilaterally change the conditions or appropriate the funds, as the program enforces compliance with the terms, and all actions are recorded immutably in the ledger [2].

Consequently, smart contracts are capable of enhancing efficiency (as they accelerate transactions and eliminate bureaucracy), as well as trust (as they remove the need to "take someone's word for it" and replace it with trust in code and the network).

Application of Blockchain: Global Experience. The authors' scientific investigation has established that, as of today, blockchain has become widely adopted across numerous industries, demonstrating its potential to solve complex problems and its capacity to transform traditional systems of stakeholder interaction. In turn, the authors have concluded that smart contracts are not merely "digital agreements", but rather integrated managerial mechanisms without analogues, which enable the automation of key processes of economic activity, namely: from application to verification; from fund allocation to monitoring and reporting; and from transparency to sustainable trust. Below are presented successful benchmarks of their application in various countries across the world.

In the domain of public administration, Estonia stands out as a prominent example and is regarded as a pioneer in the application of blockchain technology for securing governmental data. Since 2008, the country has implemented the KSI Blockchain technology to protect data in sectors such as healthcare, the judicial system, and business registries. This enables citizens to control access to their personal information and ensures transparency in public sector processes [13, 14].

Georgia is also among the first countries to have integrated blockchain technology into its property rights registration system (since 2016, in cooperation with Bitfury). As a result, the Georgian land registry system has become more efficient, and the opportunities for fraud related to property ownership have been virtually eliminated. This innovation has provided safer conditions for real estate investment by reducing bureaucratic barriers and associated business risks.

It is also important to mention the United Arab Emirates and their strategic initiative, the "Emirates Blockchain Strategy 2021". The UAE set an ambitious goal of transferring 50% of all government transactions onto a blockchain platform by the target year outlined in the strategy. This includes operations such as visa issuance, bill payments, and license renewals. An undeniable advantage is that the implementation of blockchain enables a significant reduction in paper-based workflows, cost savings, and a marked improvement in the efficiency of public services [15].

Switzerland represents a prominent example of the application of blockchain technology used for electronic voting at the local level, thereby ensuring the transparency of vote counting as well as the protection of voters' data. It should be emphasized that such a governmental initiative contributed to an increased level of public trust in the electoral process and reinforced political stability, which, in turn, attracts investment flows and stimulates economic activity [16].

Governments of several countries have also introduced similar models aimed at ensuring the safety of food and pharmaceutical products, establishing a system of transparent monitoring from the producer to the retail distributor. Notably, China was among the first countries to implement blockchain in the national food safety system. In 2016, Walmart, in collaboration with IBM, JD.com, and Tsinghua University, launched a pilot project to track pork supply chains using blockchain technology. The primary objective of this project was to enhance the transparency and safety of food products. Subsequently, Walmart expanded the application of blockchain to track other food items, including mangoes and shrimp, which enabled the reduction of product traceability time from several days to a matter of seconds [17].

The European Food Safety Authority is currently actively supporting the implementation of the Food Safety Market (FSM) program, which is aimed at transforming the food certification market in the European Union member states through the use of Big Data and blockchain technologies. The objective of the program is the establishment of an industrial-scale data platform for the digitalization of food certification processes [18].

Another illustrative example is the United States. In 2020, the U.S. Food and Drug Administration (FDA) introduced the "New Era of Smarter Food Safety Blueprint", which encourages the application of blockchain technologies to enhance the traceability of food products. As can be observed, the aforementioned examples demonstrate the growing interest and practical application of blockchain technologies by governments of various countries to ensure safety and transparency within food supply chains. Undoubtedly, the implementation of such systems significantly contributes to increased consumer trust, a reduction in counterfeiting risks, and an overall improvement in product quality [19].

In the financial sector, the emergence of digital bonds and tokenized assets opens up new opportunities for capital raising. For instance, the World Bank issued the first blockchain-based bonds in 2018 (the Bond-i project), demonstrating that major investors are willing to engage with decentralized platforms to enhance the efficiency and speed of settlements [20]. The European Investment Bank (EIB) launched the issuance of digital bonds on the blockchain. In April 2021, the EIB announced the issuance of two-year digital bonds totaling 100 million EUR using the public Ethereum blockchain. This initiative demonstrated the potential of blockchain technology in ensuring transparency and efficiency in the process of issuing and managing debt instruments [21]. It is also worth noting the experience of the Polish company Beesfund, which developed the TokenBridge platform. This platform enables the tokenization of shares, bonds, and other financial instruments, facilitating their free circulation on the blockchain. It should be emphasized that this contributes to the

democratization of investment and the expansion of access to capital for small and medium-sized enterprises [22].

It is particularly important to emphasize the role of blockchain technology in combating corruption and enhancing transparency – a factor that is especially crucial for developing economies. For example, in Colombia, blockchain is used to increase transparency in public procurement. A pilot project in Medellín applies this innovation to monitor supplier selection processes in the school meals program, thereby ensuring transparency and preventing corruption [23].

Another example of blockchain implementation concerns public procurement in Peru. In 2018, the Peruvian government agency "Perú Compras" entered into a partnership with the blockchain startup Stamping.io to develop a transparent procurement system executed by the state. This system utilizes the LAC-Chain blockchain network, initiated by the Inter-American Development Bank (IDB) for the purpose of digital registration and verification of procurement orders. Thus, it creates an immutable chain of records that guarantees the authenticity of procurement data. According to the published Decrypt report, the aforementioned blockchain system aims to prevent data manipulation and unauthorized actions during the contract conclusion process. During the pilot phase, the system processed between 500 and 1,000 orders per day, demonstrating high effectiveness and scalability potential [24].

Undoubtedly, the authors' research primarily focuses on innovative technologies applied in Ukraine. One such "weapon" against corruption is the ProZorro.Sale electronic public asset sale system, launched in the country after the Revolution of Dignity, which has become one of the symbols of transparency. In its first year, it facilitated the sale of public assets (ranging from non-performing bank loans to real estate) amounting to approximately 210 million USD, which is comparable to the total volume of privatization over the previous five years [25].

It should be noted that although the ProZorro system itself was not initially based on blockchain technology, elements of blockchain have subsequently been integrated into the system to enhance the level of trust: in particular, certain trading data is now duplicated in a distributed ledger, ensuring the impossibility of retroactively altering tender information. Despite the persisting challenges in the sphere of public procurement, the implementation of digital solutions, including components of blockchain technologies, contributes to improving the level of transparency and openness of information regarding tendering procedures. This creates conditions for the reduction of corruption-related risks and strengthens the control mechanisms from civil society and relevant stakeholders [26]. For businesses, such conditions – although they do not entirely eliminate corruption – nonetheless establish a more transparent environment and contribute to increased competition and fairness in

the allocation of public contracts, which, in turn, reduces transactional costs and broadens the pool of directly interested participants.

According to the authors' conviction, the implementation and scaling of smart contracts in Ukraine should reasonably be considered as an effective transmission mechanism (transfer factor) and simultaneously a catalyst for the intensification of economic development, particularly in the field of investment activity. Their implementation can ensure the automation of processes while eliminating the human factor at critically important decision-making points. All of the above, it is logical to assume, will significantly enhance transparency and contribute to the formation of institutional trust, which, in aggregate, will create favorable conditions for the attraction of both domestic and international capital.

Blockchain in Ukraine: Potential and Achievements. Ukraine has established itself as a technological innovator in the field of digital public services, notably through the implementation of the "Diia" system. Launched in 2020, Diia is a mobile application and web portal developed by the Ministry of Digital Transformation of Ukraine, allowing citizens to access over 130 government services online, including digital identification documents and business registrations. Furthermore, Ukraine is recognized as one of the most cryptocurrency-friendly countries. In September 2021, the Verkhovna Rada (Ukrainian Parliament) adopted the Law "On Virtual Assets", which officially recognizes digital assets and establishes a legal framework for their circulation. This law defines virtual assets, determines market regulators such as the National Bank of Ukraine and the National Commission on Securities and Stock Market, and sets conditions for the registration of virtual asset service providers [27, 28]. Although the full implementation of the law required additional amendments to the tax code, the adoption of the law itself demonstrates Ukraine's readiness and commitment to integrating digital financial instruments into its economy.

According to the authors' perspective, the war that began in Ukraine in February 2022 became a catalyst for the widespread use of blockchain: state structures and volunteers began to attract assistance through cryptocurrencies, bypassing lengthy banking procedures. Already on the second day of the war, the Ministry of Digital Transformation published official crypto wallets for financial assistance and donations, and a stream of virtual assets poured in from different parts of the world. As a result, experience was rapidly accumulated in handling large volumes of cryptocurrencies, as well as their conversion and targeted expenditure on defense needs and humanitarian projects. The acquired experience confirmed that virtual assets can facilitate fundraising and make the process extremely fast and transparent. It is also significant that initiatives for integrating blockchain into post-war reconstruction are already being formed in Ukraine. Thus, a group of people's deputies and experts

from the association "Blockchain4Ukraine", together with the public union Virtual Assets of Ukraine (VAU), developed and presented a roadmap for the implementation of blockchain and Web3 technologies in Ukraine in November 2022 [3, 29].

One of the key directions of the project is the launch of a decentralized real estate and land registry based on blockchain – as a foundation for transparent and secure handling of property rights in the process of restoring housing destroyed as a result of military actions. In February 2023, VAU and the State Service for Special Communications signed a memorandum of cooperation for the implementation of this blockchain real estate registry project [3, 29].

Another area worthy of separate mention is the Blockchain4Grain initiative, aimed at solving the problem of mined and contaminated agricultural lands in Ukraine, polluted with explosive remnants of war and other contaminants. The project involves the implementation of blockchain technologies for tracking and financing demining operations in the de-occupied regions (including Kherson, Mykolaiv, and Zaporizhzhia oblasts), as the revival of Ukraine's role as a global food supplier largely depends on this.

Thus, according to the authors' belief, the potential application of blockchain technology and the introduction of smart contracts in Ukraine appears to be quite multifaceted: from the restoration of industrial facilities and residential infrastructure to the revival of the agricultural sector, from public services (including the issuance of blockchain-based educational diplomas) to energy infrastructure (in this case, referring to the "Blockchain4Energy Project" in cooperation with the Ministry of Energy) [9].

All these initiatives are united by a common goal – the digital transformation of Ukraine's post-war economy based on the principles of transparency, openness, and trust. In the following sections of the monographic study, the authors will explore how exactly blockchain technologies can serve as a driver for attracting investment, and a project-based blockchain model will be presented to support the recovery of war-affected settlements.

4.3 Methodological model of the study

Approach and Research Methods. This study is systemic and comprehensive in nature, combining theoretical analysis, exploration of applied cases, and the development of a conceptual model. The methodology is based on an interdisciplinary approach: it involves tools of economic analysis (assessment of the influence of trust and transparency on investment activity), elements of information technology (analysis of the architecture of blockchain-based solutions), as well as methods

of content analysis of legal and regulatory documents, and secondary data sources. A significant component of the methodology was the semantic analysis of key terms and concepts related to the theme of the monographic research. This analysis allowed the identification of the key semantic nodes of the topic and the determination of the central semantic axis around which the core concepts are structured. The central axis of the study is the concept of "transparency in investment processes during the post-war recovery of Ukraine" – it lies at the core, as it connects technological aspects and economic outcomes (i.e., how technical transparency and the scaled implementation of smart contracts will contribute to economic trust and the activation of investment activity). Surrounding this axis are the following semantic nodes: Blockchain technologies; Smart contracts; International investments; Post-war recovery; Remediation; Revitalization; Anti-corruption control; Digital transformation. Each of these concepts was analyzed in terms of definitions and interrelations (**Fig. 4.2**).

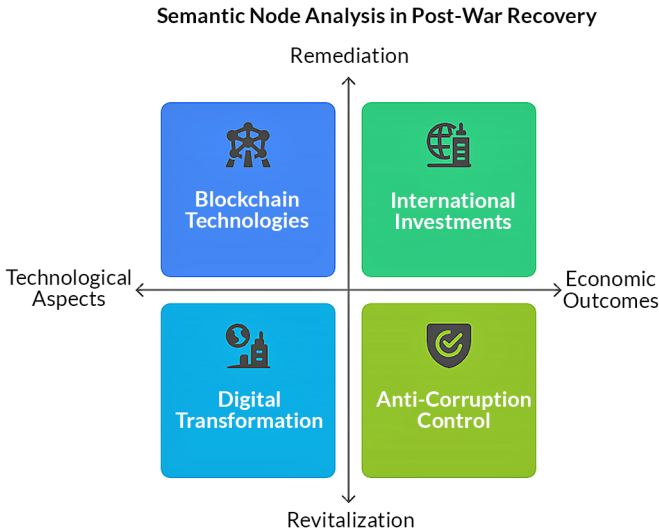


Fig. 4.2 Key semantic nodes of the methodological research model

Blockchain technologies and smart contracts represent the consistent foundation of the study, which predetermine the very fact of investment inflow. Their logical connection with investment activity is manifested through the concept of investor trust in the project and the notion of potential effectiveness, namely: implementation of these technologies → increase in transparency level → strengthening of trust

among all participants of recovery projects → growth of investment activity in the restored territory.

International investments – in the context of this study, are understood as both foreign direct investment (FDI) and donor funding, loans from international organizations, assistance from individual benefactors and Ukrainian diasporas of various types, among others. Logical linkage: international capital will be invested under the condition of a favorable climate and an established relationship system, which includes transparency at every stage of financial allocation for post-war recovery based on the rule of law.

Post-war recovery is the general context of this comprehensive and systemic study, which encompasses all types of work related to the reconstruction and restoration of destroyed economic facilities, infrastructure, housing, and social objects in territories affected by military actions. It is inextricably linked to the need for investments of a technical, technological, informational, humanitarian, and other nature, as the recovery process requires a diversity of various types of resources and technologies. The logical connection with the necessity of implementing digital technologies is driven by the need to apply non-standard solutions and modern approaches to the management of remediation and revitalization processes.

Remediation is a concept denoting a set of measures aimed at the ecological and socio-economic restoration of war-affected territories. In the context of Ukraine, it includes the elimination of military contamination, rubble removal, demining, restoration of soil, water, and air quality, as well as the reconstruction and remediation of destroyed facilities.

Revitalization, as understood by the authors, refers to the rebirth or return to active social and economic life of communities and settlements following remediation activities. It includes the restoration of social and cultural environments, infrastructural objects within populated areas, and the creation of conditions for the return of businesses and population.

According to the authors' belief, these two concepts are logically interconnected: remediation serves as the initial stage (specifically, the cleansing of the territory after the cessation of military activities and the elimination of all types of contaminants, as well as preparing the area for further revival), which is followed by revitalization – a return to normal life (economic, cultural, and social) on the recovered territories.

Logically, both stages require substantial investment and effective management of the abovementioned projects, which, in turn, necessitates ensuring transparency and control. Therefore, they are included in the semantic field of the study as crucial directions where blockchain systems and smart contracts can be employed to guarantee the targeted allocation of all types of resources.

Anti-corruption control plays the role of a critical condition necessary for ensuring investor trust. Post-war recovery projects, regardless of their potential profitability, will not attract investment if funds are embezzled through corrupt schemes and non-transparent regulation. Blockchain and smart contracts potentially serve as instruments of anti-corruption monitoring (transactions cannot be hidden or altered, contract terms are subject to automatic execution and are publicly accessible for control). Therefore, the logical sequence is unambiguous: Digital technologies → Anti-corruption control at all stages of project implementation → Stakeholder trust → Investment inflow.

Digital transformation encompasses all IT innovations and digital solutions that may be applied to address the research objectives. Semantically, it is important that blockchain fits into the general trend of the digital transformation of Ukraine's recovery governance. The logical connection is as follows: Digital tools (including blockchain) → Transparent management of remediation and revitalization of war-affected territories → More efficient and rapid recovery → Increased attractiveness for investors. It is crucial to emphasize the fact that remediation and revitalization are dimensions of post-war recovery that are critically dependent on trust and control, and therefore their analysis through the prism of blockchain technologies is of paramount importance and significance [30].

4.4 Analytical assessment of the role of blockchain technologies in stimulating international investment activity in post-war Ukraine

Financial resources required for post-war recovery of Ukraine. In order to understand how blockchain can influence investment activity, it is first necessary to outline the problem field of this process. The post-war recovery of Ukraine, in terms of its scale and required resources, is often compared to a new "Marshall Plan". However, unlike post-war Western Europe in the mid-20th century, modern Ukraine faces not only economic difficulties but also a trust deficit.

Even in the presence of a number of positive reforms (such as the ProZorro system, NABU, Diia, etc.), Ukraine continues to be perceived as a country with a high level of corruption due to a combination of factors: weak judicial institutions, oligarchic influence, low level of law enforcement, and a scandalous media environment.

According to the CPI index data presented above (Fig. 4.3), Ukraine, with a score of 35, is positioned below the global average, which indicates structural and persistent corruption risks.

For comparison: the Republic of Poland scored 54 points (in 2024), the Republic of Lithuania – 61, the Federal Republic of Germany – 78, the Kingdom of Denmark is the leader with a score of 90.

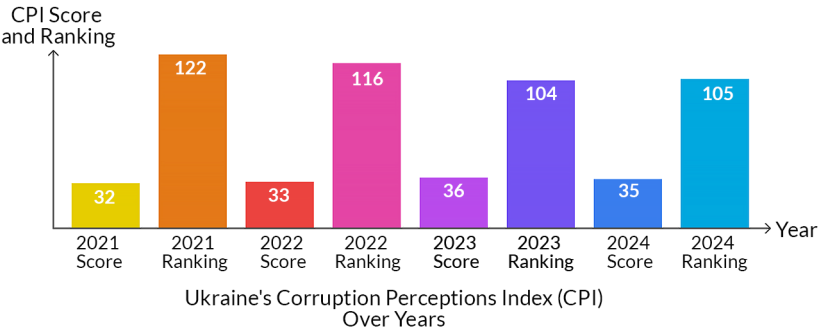


Fig. 4.3 Dynamics of Ukraine's position in the Global Corruption Perceptions Index, 2021–2024

It should be emphasized that the higher the CPI score, the lower the perceived level of corruption and the more favorable the investment and institutional environment in the country (**Fig. 4.4**). This is critically important for building trust among investors, donors, and international partners.

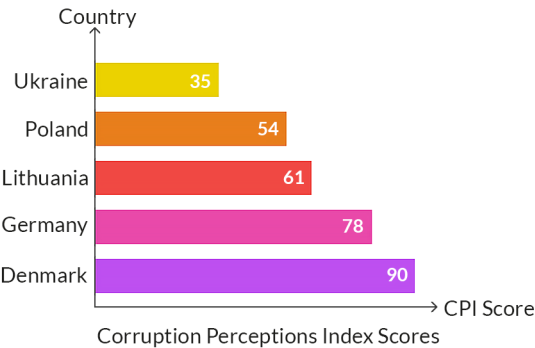


Fig. 4.4 Ukraine's place in the Global Corruption Perceptions Index, 2024

Despite the enormous international support, donors and investors expect concrete steps from Ukraine in the context of ensuring the transparency of resource utilization, as they understand that "every dollar must reach its intended goal".

Western partners explicitly link the volume of aid to the progress of ongoing reforms in Ukraine.

In this regard, it is worth highlighting the launch of the pilot project in 2023 – the Unified Digital Recovery Project Management System (DREAM platform), which is intended to ensure a full cycle of open monitoring – from the submission of project applications to tenders, execution of works, and payments – with open data available at each stage of implementation [31]. It is envisaged that the DREAM system will aggregate information from all existing sources and make it publicly accessible – something that has not previously existed in Ukrainian administrative practice. According to the unequivocal opinion of experts, it is critically important that all recovery projects be transferred into this system to guarantee maximum transparency and provide investors with a comprehensive picture of territorial remediation and revitalization [32].

Nevertheless, even in the presence of political will and implemented digital platforms, unfortunately, other persistent risks for investors still exist. Corruption may manifest not only through direct embezzlement of funds but also during the stages of reconstruction and remediation works (for example, overpricing of construction materials, collusion in tenders, failure to comply with standards, etc.). Investors are fully aware of the aforementioned risks. Historically, Ukraine has suffered from a lack of foreign direct investment (FDI), largely due to its negative reputation concerning corruption and the weakness of state institutions responsible for counteracting such phenomena.

Between 2021 and 2024, Ukraine experienced significant fluctuations in the inflow of foreign direct investment (FDI), driven by both internal factors and global economic trends. A detailed analytical assessment of the dynamics of FDI in the Ukrainian economy during this period is presented below (Table 4.1).

Table 4.1 Dynamics of FDI in Ukraine during the period 2021–2024

Year	FDI Volume (billion USD)	% of GDP
2021	7.95	4.1
2022	0.22	0.3
2023	4.81	2.7
2024	0.16 (Q3)	The data for the entire year has not yet been determined

Source: the data in the table was taken from sources [34–36]

As can be seen from the table data, in 2022 there was a sharp decline in the total inflow of FDI to 0.22 billion USD, which accounted for only 0.3% of GDP. This dramatic decrease in the scale of investment activity was associated with the outbreak

of full-scale war, which led to capital outflows and the suspension of already launched projects. In addition, global trends, including the rise in energy and food prices, further exacerbated the negative impact on the overall investment climate. However, already in 2023, an increase in FDI volume was recorded, reaching 4.81 billion USD (which accounted for 2.7% of GDP, factual note). It should be noted that a significant part of these investments came from reinvested earnings rather than new capital inflows. According to the National Bank of Ukraine, in 2023, reinvested earnings accounted for approximately 75% of the total volume of foreign direct investment.

The impact of blockchain on investor trust. Blockchain technologies can provide unprecedented transparency of financial flows, which will be the key to solving the challenges of attracting investment capital to Ukraine. If all transactions within investment projects are recorded in a public (or accessible to regulatory bodies) blockchain, then any interested stakeholder – from an international auditor to an ordinary citizen of Ukraine – will be able to trace the movement of financial resources from the source to the final recipient.

For instance, in the case of the above-mentioned recovery platform functioning on blockchain, the process would look as follows: the investor does not transfer funds to a regular bank account, but rather to the address of a project-specific smart contract. Then the smart contract automatically transfers these funds to specific contractors as they complete their work, and each such payment is reflected in the ledger with an indication of the amount, time, recipient, and justification for the transaction. No "hidden streams" of funds can go unnoticed, as the blockchain does not allow for payments "around the system" – every operation must be confirmed by the network. This sharply contrasts with the traditional system, in which funds may be moved between accounts of various subcontractors, offshore entities, etc., and only ex-post audit may (or may not) detect traces of misuse of resources. Essentially, blockchain enables the integration of the entire financial picture of the recovery process. According to the authors, the ideal implementation of the remediation and revitalization strategy for Ukraine's territory involves the complete elimination of the human factor in the allocation of financial and other resources – which is equivalent to the elimination of corruption.

The next equally important aspect is the enhancement of accountability. Since blockchain records are immutable, any instance of misuse of funds remains in the historical ledger and can be proven. This in itself acts as a preventive measure: knowing that transactions are open and indelible, participants are less inclined to commit violations. In addition, smart contracts allow for the codification of rules and conditions for fund utilization. For example, international partners may insist that their investments or loans be executed via smart contracts specifying clear KPI indicators. In this

scenario, funds allocated for reconstruction and remediation of war-affected territories – say, from the International Finance Corporation (IFC) – can be "unlocked" in tranches only upon the achievement of specific construction stages. These stages may be certified by an independent engineering inspection, the results of which are uploaded into the blockchain. If the conditions are not met, the smart contract may return the unused funds to the investor upon expiration of the contract term. This creates confidence among international stakeholders that their money will not disappear without trace – it will either be spent in a targeted manner or remain fully preserved. Finally, an equally critical aspect is the reduction of transaction costs and time. As is well known, international bank transfers – especially involving multiple parties – are usually time-consuming and involve significant commission expenses. Blockchain, on the other hand, operates 24/7 without borders: transfers in cryptocurrencies or stablecoins can be completed within minutes.

This is extremely important, especially in conditions where funds are urgently needed. As mentioned earlier, the war in Ukraine has already demonstrated the advantage of such a system: millions of dollars in cryptocurrency were mobilized and delivered to recipients within mere hours or days, whereas traditional aid required weeks to arrive [5].

It should be emphasized that after the end of active hostilities, the factor of time and the speed of recovery will have colossal significance. This refers to the prompt elimination of contaminants in water resources, the reconstruction of critical infrastructure facilities, or housing before the onset of cold weather [37]. In this case, rapid financing enabled by blockchain significantly increases the likelihood that projects will be implemented on time and, consequently, enhances the motivation of potential investors (as projects are not "frozen" due to funding delays and the completion of project implementation is not postponed). In addition to the aforementioned, the reduction in the number of intermediaries (such as banks, insurance agencies, etc.) substantially saves both money and time. For international investors, this means a more efficient use of their capital (in this case, a greater "return" on every dollar invested), which, in turn, encourages them to participate in a greater number of projects.

The final and most significant aspect is the emergence of innovative capital investment mechanisms and, consequently, new opportunities. Blockchain technologies introduce novel methods of investment that were previously inaccessible. One such method is the tokenization of assets. As highlighted in the study by Ukrainian economists M. Riabokin and Ye. Kotukh, Real World Asset (RWA) tokenization can serve as a powerful catalyst for attracting capital into Ukraine's economy in the post-war period [38]. The essence of RWA tokenization, as described by the authors, involves transforming real assets – such as real estate, infrastructure facilities, land

plots, and even future production outputs of enterprises – into digital tokens on the blockchain. These tokens confer ownership rights or shares in the assets and can be freely exchanged or sold to investors worldwide. For Ukraine, which possesses a substantial volume of underutilized assets with low economic efficiency, tokenization can significantly lower entry barriers for investors and enhance the liquidity of these assets. The study emphasizes that implementing RWA tokenization can become a strategic tool for Ukraine's post-war reconstruction and digital economic transformation, facilitating the creation of new investment instruments and modernizing the country's financial infrastructure.

This resembles the issuance of securities but on decentralized infrastructure, without the traditional costs and delays associated with emission. Thus, it is likely that we will soon witness the creation of new investment instruments and markets, which is already supported by successful examples in global practice (such as the operation of security token platforms). M. Riabokin and Ye. Kotukh, in their study, conclude that the implementation of RWA tokenization in Ukraine opens up new channels for capital inflows, thereby contributing to the diversification of investor portfolios and enabling access to previously inaccessible assets – a factor that will be particularly relevant and significant in the context of the post-war modernization of Ukraine's financial infrastructure.

Another mechanism that, in the authors' view, holds significant development prospects in the future is the establishment of Decentralized Autonomous Organizations (DAOs) aimed at financing post-war reconstruction projects. The concept involves investor communities or interested parties forming DAOs – a set of smart contracts – to pool funds into a common treasury and collectively decide which projects to invest in (for example, through blockchain-based voting).

Such a mechanism provides a tangible opportunity for the Ukrainian diaspora in countries like Canada and the USA to directly invest in specific projects (including the restoration of schools, hospitals, monuments, etc.) in a crowdfunding format managed by smart contracts, thereby mitigating the risks of fund misappropriation by organizers. It is noteworthy that this mechanism has been tested: in 2022, Ukraine DAO was established, which raised 6.75 million USD through an NFT auction of a digital Ukrainian flag to support Ukraine's war efforts. The proceeds were directed towards humanitarian needs, demonstrating the potential of DAOs in mobilizing resources for targeted causes [39]. According to the authors' vision, similar DAOs could be created to facilitate the reconstruction of the community concerned with Ukraine's recovery.

Summarizing this analytical section, the following can be concluded: the implementation of blockchain technologies and smart contracts possesses significant

potential and a multiplicative effect in stimulating economic, including investment, activity. The direct effect of their application is the increase in trust among all participants and stakeholders, the reduction of risk levels, as well as the expansion of financing mechanisms for projects. In the context of Ukraine, their scaling across all spheres of socio-economic activity can stimulate capital inflows. The indirect effect will be the improvement of the reputational image and investment climate, which also correlates with the willingness of foreign actors to initiate partnerships and participate in reconstruction projects. For post-war Ukraine, where the demand for resources is colossal and the competition for them is high, the use of blockchain technology in all its manifestations may become a competitive advantage.

Analysis of the multi-aspect systemic functionality of blockchain and smart contracts. Based on the in-depth scientific analysis presented above, it is reasonably possible to assert that blockchain technologies and smart contracts perform a multi-aspect systemic function in the context of post-war recovery in Ukraine, especially in the direction of stimulating international investment activity. Below is an expanded and detailed characterization of their role, presented as logically interconnected provisions, namely:

1. Blockchain and smart contracts act as a *mechanism* for ensuring transparency and accountability, which allows the weaknesses of traditional project management systems to be mitigated (in our case – investment-related).
2. They represent a *method* of digital verification of actions, in which: full control over compliance with pre-established conditions is executed (through the use of software code); legal and technological justification for the distribution of financial resources is achieved; opportunities for seamless integration into project management methodology with linkage to KPIs and project implementation phases are ensured.
3. Blockchain and smart contracts are a technological *tool* for investment management and project implementation, which: allows the investor to "see" the use of their funds at each stage; increases trust through step-by-step, consistent, and immutable records; reduces transaction costs; significantly optimizes and accelerates the pace of operations; can be seamlessly implemented as a module in existing digital platforms (for example, Camunda + blockchain + Streamlit).
4. These technologies function as a *lever* for institutional changes, which: transform the principles of working with donor and investment capital; help to reduce corruption levels; strengthen Ukraine's position as a trustworthy partner; facilitate decision-making on the part of international investors, IFIs, diaspora, and the private sector.
5. Blockchain and smart contracts serve as a *transfer factor* of trust, which connects: the intentions of the investor ↔ with the implementation process ↔ with final results; legal transparency ↔ with digital immutability and, accordingly,

stability; off-chain processes ↔ with on-chain fixation (for example, DAO-investment, tokenization).

In addition, within the context of this scientific study, blockchain and smart contracts:

- form the foundation for creating digital ecosystems for the remediation and revitalization of war-affected territories (including DREAM, Blockchain4Grain, Blockchain4Energy, etc.);
- ensure infrastructural compatibility with European digital standards, such as EBSI, eIDAS 2.0;
- create new formats of institutional interaction: DAO, RWA tokenization, digital bonds (including EIB, Bond-i, Beesfund, etc.).

Thus, within the framework of the authors' monographic study, blockchain and smart contracts simultaneously function as a mechanism of institutionalization of trust, a method of digital transformation, a tool of anti-corruption control, a lever for strengthening investment activity, and a transfer factor for the transition from reputational risk to a transparent and controllable financial architecture of recovery.

4.5 Project model of a blockchain system for post-war remediation and revitalization in Ukraine

General provisions and requirements. The project model developed within the framework of this study envisions the creation of an integrated blockchain-based platform for managing recovery projects. This platform is intended to support remediation projects at the national scale with an initial pilot launch in one of the most affected settlements (including, among others, demining, environmental cleanup, ecosystem restoration, etc.) and revitalization projects (including, among others, the construction and reconstruction of housing, infrastructure, social, cultural, and household facilities for the population, economic revival of territories, etc.). The key objective of the proposed system for implementation is to ensure full transparency and accountability at all stages of the project life cycle, from planning to completion, thereby strengthening the trust of both external investors and the local community.

Justification. The war has destroyed not only industrial facilities and infrastructures but also the social life of communities that lived in specific settlements (houses, social, cultural, and household facilities, household plots, domestic farming, business facilities, etc.). Undoubtedly, revitalization is impossible without first ensuring physical security. Thus, a logical sequence of necessary actions for implementation is built: Assessment and identification of war-inflicted damage, destruction, and

needs → A set of remediation measures (demining and cleaning of territories from the consequences of military activities) → Cleared lands/territories → Restoration of infrastructure → Return of the population → New economic activity.

Project goal. The goal of the project "Smart-Invest: Blockchain-Based Remediation and Revitalization through Smart Contracts in Post-War Recovery (SIBReS)" is to create an integrated digital model for managing post-war recovery (using the example of the village of Chornobaivka in the Kherson region), which will enhance the investment attractiveness of the territory through the integration of blockchain technologies and smart contracts as mechanisms of institutional trust, transparency, and effective investment process management. The project is aimed at stimulating the inflow of international investments, including foreign direct investment (FDI), donor funding, and the participation of Ukrainian diasporas from various countries (Fig. 4.5).

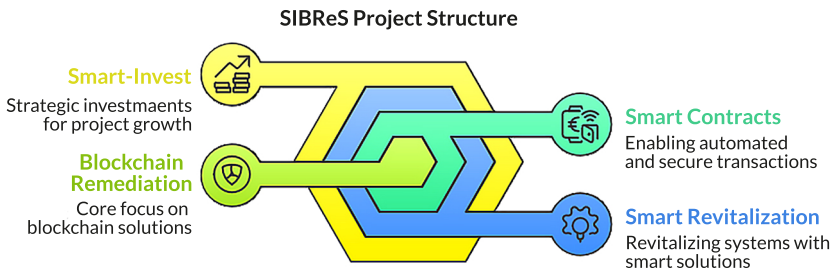


Fig. 4.5 Smart-invest project characterization: blockchain-based reconstruction and revitalization through smart contracts in post-war reconstruction (SIBReS)

Expected results. The SIBReS project will serve as a next-generation model for managing the recovery of territories affected by military activity – synthesizing advanced informational, technological, economic, and social approaches. It is expected that the implementation of this project will contribute to the formation of a new digital culture of transparency and trust, which is currently of critical importance in the context of the rapid and effective restoration of Ukraine's socio-economic development. According to the authors' conviction, the successful launch of the SIBReS project will enable the scaling of similar initiatives across the entire territory of the country, which, in turn, will have a positive impact on the investment climate and the international image of the state – demonstrating its readiness for the active implementation of innovative technological solutions.

The stages of the project are presented in **Table 4.2**.

Table 4.2 Stages of the project "Smart-invest: blockchain-based remediation and revitalization through smart contracts in post-war recovery (SIBReS)"

Stages	Component	Key Technologies/Tools
1	Assessment and Identification of Remediation and Revitalization Targets	Geo-analysis, satellite imagery, damage assessment inspections, registry of destroyed territorial assets
2	Remediation	Demining, mechanical and biological cleanup of sites and areas, environmental audit
3	Project Application, Investor Search, Donor Funding	Project creation on the platform, investor registration (FAQ, EBRD)
4	Contractual Module	Smart contracts on Ethereum/Binance Smart Chain + integration with ProZorro
5	Implementation Monitoring	IoT sensors, GPS, satellite verification, IPFS storage, auditing
6	Revitalization	Reconstruction of housing, social, cultural and utility infrastructure, road and communication networks, economic reactivation, MSME development support
7	Transparent Reporting	Visualization through blockchain interface, dashboard for investors, financial donors, and local residents

Project advantages:

- *modularity*: each of the aforementioned project stages represents a separate smart contract block. The transition to the next stage will only be possible upon confirmation of the previous one (audit → validation → activation of the next tranche);
- *participation of local residents*: possibility of feedback through DAO mechanisms (including voting by residents on the platform regarding the order of implementation of recovery projects in the settlement of Chornobaivka);
- *integration with state registries*: all information on the restoration status of the settlement, including all objects, will be digitized and integrated with the "Diia" system, the open data platform data.gov.ua (for the analysis of open environmental data, namely for the monitoring of air, water, and soil pollution), the Unified State Land Cadastre platform, and others.

Starting point and rationale for selection. Chornobaivka is one of the symbolic and significant settlements in the context of the full-scale war in Ukraine. It was frequently mentioned in the media as one of the epicenters of military operations and artillery shelling, which were associated, among other things, with the location of the Kherson airport and a military helicopter unit in Chornobaivka.

Key reasons for selecting this settlement as a pilot zone Include:

- *level of destruction:* according to assessments, over 80% of the residential housing stock has been destroyed; the private sector has been decimated, and no surviving social, cultural, or public service facilities remain;
- *scale of contamination:* the surrounding fields and areas of the settlement are heavily mined; remnants of explosive ordnance, military equipment, and other hazardous elements have been recorded;
- *diversity of post-war recovery tasks:* these include a wide range of activities – from demining operations and environmental decontamination to the construction and reconstruction of residential, industrial, and infrastructural facilities, as well as the restoration of social, cultural, and public service infrastructure;
- *high potential* for multi-sectoral recovery due to strategically significant geographical localization and other favorable factors.

Development potential and scenarios for post-war revival.

Before the war, the area featured:

- a high concentration of agro-industrial production;
- a logistics zone including an adjacent airport, highways running along the settlement, and the "Chornobaivka Station" railway terminal;
- a well-developed private residential sector with high building density, along with fully functioning infrastructure for social, cultural, and public service needs.

After de-occupation (as of today):

- severe environmental and infrastructural damage has been inflicted;
- the production potential has been almost completely destroyed;
- the system of governance and resource distribution has been disrupted;
- significant destruction of residential infrastructure has occurred;
- substantial decline in population and loss of labor potential (as of July 31, 2024, the settlement had approximately 5,000 residents, compared to over 17,000 before the war) [40].

Post-war development potential:

- extensive opportunities for the development of solar energy – the southern geolocation makes Chornobaivka a promising localization zone for the advancement of renewable energy;
- restoration of the agro-industrial sector of the economy – after land remediation, implementation of programs in crop production, agro-processing, and agro-technologies is feasible;
- opportunities for tourism development (including agro-tourism and eno-tourism) – development of environmentally friendly farms, ethno- and agro-tourism routes, including the implementation of tokenized investment projects;

- development and strengthening of transport and logistics potential – restoration of the transport hub as a regional and national transit node;
- development of adjacent sectors linked to the region's core specializations – primarily through support for small and medium-sized business development;
- multiplicative effect as a result of revitalization achievements – population return, revival of social and cultural life, and the full functioning of the territorial socio-economic system.

Digital platform layout of SIBReS.

The authors have structured the general layout of the project, which is presented in the tables below (**Tables 4.3, 4.4**).

Table 4.3 General architecture of the SIBReS platform

Element	Description	Role and Significance
Frontend (UI/UX)	User interface for all user categories, including a mobile version	Provides access to the platform, facilitates participation in the recovery project, and enables interaction within the system (investors, donors, contractors, citizens, etc.)
Backend	Server-side logic: routing, API, caching, embedded business rules	The core of data processing and project management, enabling system scalability
Blockchain Layer	Decentralized transaction recording and storage, smart contracts, IPFS	Ensures transparency, data protection, automation of funding flows, and investor trust
Integration Modules	Interfaces with external systems: ProZorro, Diia, UNITED24, ArcGIS, satellite data	Expands platform capabilities by enabling synchronization with analytical services and national registries
Database	PostgreSQL + TimescaleDB + ElasticSearch for storage and analytics	Stores structured metadata and provides fast access to information and time series data

Table 4.4 Characteristics of SIBReS project integration capabilities

Platform/Service	Brief Description
ProZorro	Full-fledged digital procurement system
Diia/Trembita	User verification, access to State Registry data
eHealth, UNITED24	Collection of data on medical and social infrastructure
IPFS + Filecoin	Reliable decentralized storage of documentation
ArcGIS/OpenStreetMap	Multi-layered geospatial analytics
Documentation	Decentralized file storage system (InterPlanetary File System, IPFS) + version control + voting system for approval
AI/ML Modules	"Before/after" comparison, anomaly detection, predictive auditing of contractors

Key modules of the platform:

1. *Project Registry Module*. Essentially, this is a unified catalog of projects with their descriptions, geotags, budgets, stages, and related documents.

Role of the module – creating a database of transparent and manageable recovery projects, reflecting their relevance and progress in remediation and revitalization.

2. *Smart Contract Module*, which is a system of automatic contracts between investors, donors, contractors, and verifiers.

Role of the module – full automation of settlements, eliminating the very possibility of misuse by ensuring logical transparency in the use of resources allocated for territorial recovery.

3. *Contractor and Inspector Module*, which represents a panel for submitting tender proposals, registering participants, and forming reports.

Role of the module – creating a healthy competitive environment that promotes increased responsibility among performers, thereby improving the quality of implemented recovery projects.

4. *Monitoring Module*, which covers, aggregates, and analyzes incoming data from drones, satellites, and sensors, with verification through AI.

Role of the module – guaranteeing objective quality control of completed works, preventing falsification and non-compliance with norms and standards.

5. *Visualization Module* – dashboards with analytics and feedback channels for project participants, including visualization of the territory recovery status.

Role of the module – ensuring accessibility of information, transparency control, and full awareness of project investors, donors, and the local population.

Project Integration. It reflects the platform's capabilities for connecting external systems. Role of integration – the ability to manage data in a unified digital space by uniting the efforts of the government, citizens, and investors.

KPI and Monitoring. *Mathematical formalization of the relationship between the implementation of blockchain technologies and investment activity, including the multiplicative effect of the remediation and revitalization project.*

A metric of the key indicators was developed for the SIBReS project, which is presented in a summarized version in **Table 4.5**.

Mathematical model of the multiplicative effect.

The formula for the overall multiplicative effect is as follows

$$I_{intl}^{+} = f(T_{blockchain}, RE, E_{rev}, D_{trust}, S_{visibility}), \quad (4.1)$$

where I_{intl}^{+} – the increase in international investment activity.

Testing the model using the example of Chornobaivka, Kherson region, including scenario simulation for the implementation of the SIBReS project.

The authors of the study launched a pilot project in a simulation environment: Camunda BPMN + Python-based smart contract model. Using Python scripts, calculations for the indicators RE , E_{rev} , D_{trust} , IAI , and the investment multiplier were performed, and the results are presented below in **Table 4.6**.

Table 4.5 Mathematical formalization of the key indicators of the project "Smart-invest: blockchain-based remediation and revitalization through smart contracts in post-war recovery (SIBReS)"

Indicator	Formula with Detailed Components	Explanation
RE (Remediation Efficiency)	$RE = \ln(A_{clean} \times Q_{ecol}) / (T_{rem} + \delta)$, where A_{clean} – remediated area (hectares); Q_{ecol} – ecological quality index (0–1); T_{rem} – time for remediation (days); δ – time stability constant	Measures the efficiency of land or water remediation. Uses the logarithmic relation of the cleaned area and ecological quality, normalized by time and stabilized for long-term comparisons
E_{rev} (Economic Revitalization)	$E_{rev} = \ln(G_{value} \times B_{yield}) / (T_{recon} + \varepsilon)$, where G_{value} – gross value added (USD); B_{yield} – business yield growth rate (0–1); T_{recon} – reconstruction time (days); ε – smoothing constant	Quantifies the effectiveness of economic recovery by integrating gross economic output and business performance gains relative to reconstruction effort and timeline
D_{trust} (Digital Trust Coefficient)	$D_{trust} = \ln(SC_{use} \times A_{audit}) / (R_{error} + 1)$, where SC_{use} – number of deployed smart contracts; A_{audit} – number of automated audits; R_{error} – recorded process errors	Evaluates the digital trust level based on smart contract usage and automated audit frequency, penalized for process inconsistencies or detected violations
$T_{blockchain}$ (Transparency Index)	$T_{blockchain} = \Sigma Confirmed / (n(1 + F_{uncertainty}))$, where $\Sigma Confirmed$ – confirmed blockchain transactions or operations; n – total registered records	Reflects the transparency of the system via the share of confirmed blockchain entries, adjusted for system-level uncertainties or non-public process elements
$S_{visibility}$ (Systemic Visibility)	$S_{visibility} = \ln(A_{access} \times P_{publicity}) / (L_{delay} + 1)$, where A_{access} – open access interfaces or data channels; $P_{publicity}$ – publicity index; L_{delay} – latency in data publication	Captures visibility and traceability of the project using the logarithmic function of open access and public awareness, adjusted for latency in publishing or interfacing data
IAI (Investment Attractiveness Index)	$IAI = (E_{rev} + D_{trust}) \times T_{blockchain} / (1 + R_{risk})$, where R_{risk} – investment risk index (expert-evaluated, 0–1 scale)	Final aggregated index for investment attractiveness combining revitalization results, trust levels, transparency, and risk control. Serves as a key output metric for investor decision-making

Table 4.6 Results of Python model calculations

Result	Value
RE (Remediation)	0.1
E_{rev} (Revitalization)	0.665
$T_{blockchain}$	0.78
D_{trust}	0.798
IAI (Investment activity)	0.747
Investment multiplier	2.03

Interpretation of the presented table results:

RE (Remediation) = 0.1 means that approximately 90% of the contaminated area is expected to be successfully cleaned. The lower this indicator, the higher the quality and depth of the remediation;

E_{rev} (Revitalization) = 0.665 reflects the multiplier value, meaning that in this case, each dollar of investment creates 0.665 USD of economic activity (through population return, SME development, and services). A value close to 1 is considered a good result for the initial stage;

$T_{blockchain}$ = 0.78 shows that 78% of transactions were processed and verified through smart contracts. This is quite a high level of transparency, which increases stakeholder trust in the project;

D_{trust} = 0.798 demonstrates the investor trust index, which is almost 0.8, reflecting a balanced combination of transparency, successful cases, and platform reputation. This is a sufficient level to motivate international partners to invest their own capital;

IAI (Investment Activity Index) = 1.03 reflects the cumulative growth of investment activity. The calculated indicator means a potential investment increase of 103% from the baseline after the implementation of the pilot project;

Investment Multiplier = 2.03 means that after the first stage of successful remediation and revitalization, the volume of investments may double.

Streamlit prototype.

For the purpose of implementing the set task, let's proceed to the creation of a Streamlit prototype. Streamlit is a Python-based framework that allows the development of interactive web applications based on data and analytical models.

In other words, a Streamlit prototype is the first working version of a digital tool (note that this is not yet the final product), which demonstrates: how the mathematical model operates; how users can interact with it; what parameter values are assumed under different scenarios.

In our case, the significance of the developed Streamlit prototype for the SIBReS project lies in: proving the operability of the mathematical model and its practical applicability; serving as a visualization tool for "what-if" scenario evaluation; preparing for the creation of an MVP (Minimum Viable Product) of the platform; forming trust among potential international investors and donors, as they can see the transparent logic that can be managed; providing an operational method for testing hypotheses.

Application within the SIBReS system.

This chart can be incorporated into the analytical module of the recovery monitoring system for: evaluating the contribution of each parameter to the final investment activity; forming predictive scenarios; selecting priority areas for project adjustments (including, for example, strengthening RE or E_{rev} depending on their impact) (Fig. 4.6).

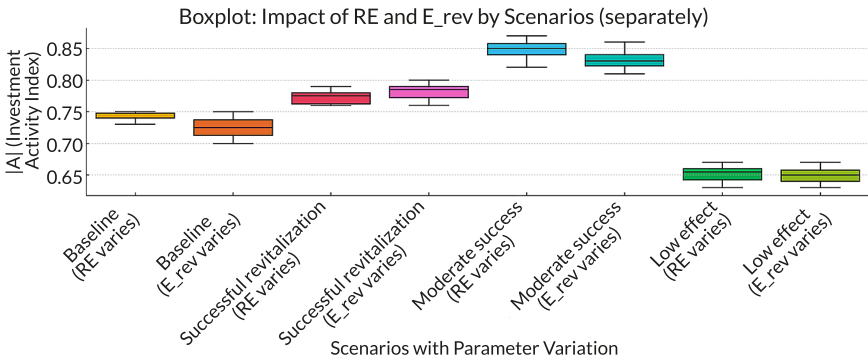


Fig. 4.6 Scenarios with parameter variation SIBReS

Let's proceed with the development of the UX layout of the SIBReS platform in the form of a schematic diagram and a prototype (Fig. 4.7).

The developed UX wireframe (user experience wireframe) of the SIBReS platform, presented as a visual schematic (interactive interface), reflects: the main structural blocks of the system (project registry, smart contracts, monitoring, visualization, etc.); user roles (investors, financial donors, contractors, government authorities, residents, etc.); logical connections between functional modules; data and action flows – from project registration to result verification and DAO voting.

Primarily, the UX wireframe is necessary for: further technical development of the project; presentation to investors and financial donors, as it provides a clear visualization of how the platform ensures transparency, verification, and resource distribution – the key to trust and funding; serving as a framework for the creation of

a Minimum Viable Product (MVP) with core functionality – the first step toward the pilot version of SIBReS; formalizing documentation, as it is used for grant applications, project roadmaps, and technical specifications.

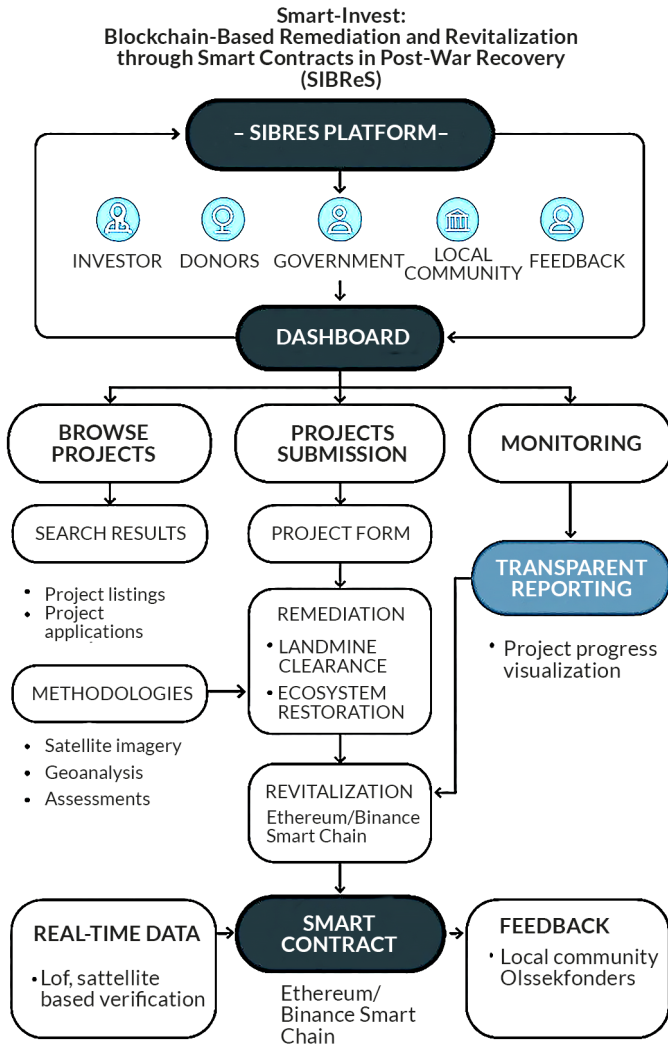


Fig. 4.7 UX layout of the SIBReS platform

The following modeling structure was used to conduct the simulation. The modeling was based on a stochastic approach using the Python programming language (specifically, the NumPy, Pandas, and Matplotlib libraries), and included 1,000 iterations per run. The purpose of the simulation was to assess the variability and resilience of the Investment Activity Index (IAI) under different economic, technological, and institutional scenarios.

The IAI was calculated using the following multiplicative formula

$$IAI = D_{trust} \cdot T_{blockchain} \cdot E_{rev} \cdot (1 + RE), \quad (4.2)$$

where D_{trust} – reflects the level of institutional trust (in the range 0.3–0.9, based on the Corruption Perceptions Index (CPI) and expert assessments); $T_{blockchain}$ – blockchain-based transparency index (in the range 0.5–0.95, based on open data from platforms such as DREAM, Diia, ProZorro, eRecovery); E_{rev} – revitalization efficiency (in the range 0.4–0.8, based on the modelled gross value added (GVA) return rate); RE – relative remediation effect (in the range 0.1–0.4, based on expert environmental impact assessment).

All parameters were randomly generated from uniform distributions within the defined ranges and subsequently normalized to ensure comparability. The ranges were selected based on open data from the World Bank, IMF, Transparency International, and empirical data from Ukraine's digital platforms.

Each simulation iteration generated one IAI value, which was visualized in the form of an "Investment Activity Cloud" (Fig. 4.8). This allowed for the observation of distribution density and general trend, confirming the overall predictive stability of the model.

This stochastic simulation made it possible to objectively analyze how changes in key parameters (such as the level of trust, remediation efficiency, revitalization effectiveness, and transparency level) influence the overall investment attractiveness of projects implemented through the use of blockchain technologies and smart contracts. The scatter plot ("investment activity cloud") of all 1,000 simulation runs, with an overlaid regression line, demonstrates that the IAI values are tightly clustered around the mean level of approximately 0.66, which confirms the high predictability and reliability of the investment process under the condition of implementing digital technologies for project management (for example, based on blockchain and smart contracts).

Thus, the previously calculated integral Investment Activity Index ($IAI \approx 0.747$) correlates with a high level of trust ($D_{trust} \approx 0.798$) and the efficiency of blockchain technology application ($T_{blockchain} \approx 0.78$), while the investment multiplier value of 2.03 indicates the presence of a strong multiplicative effect.

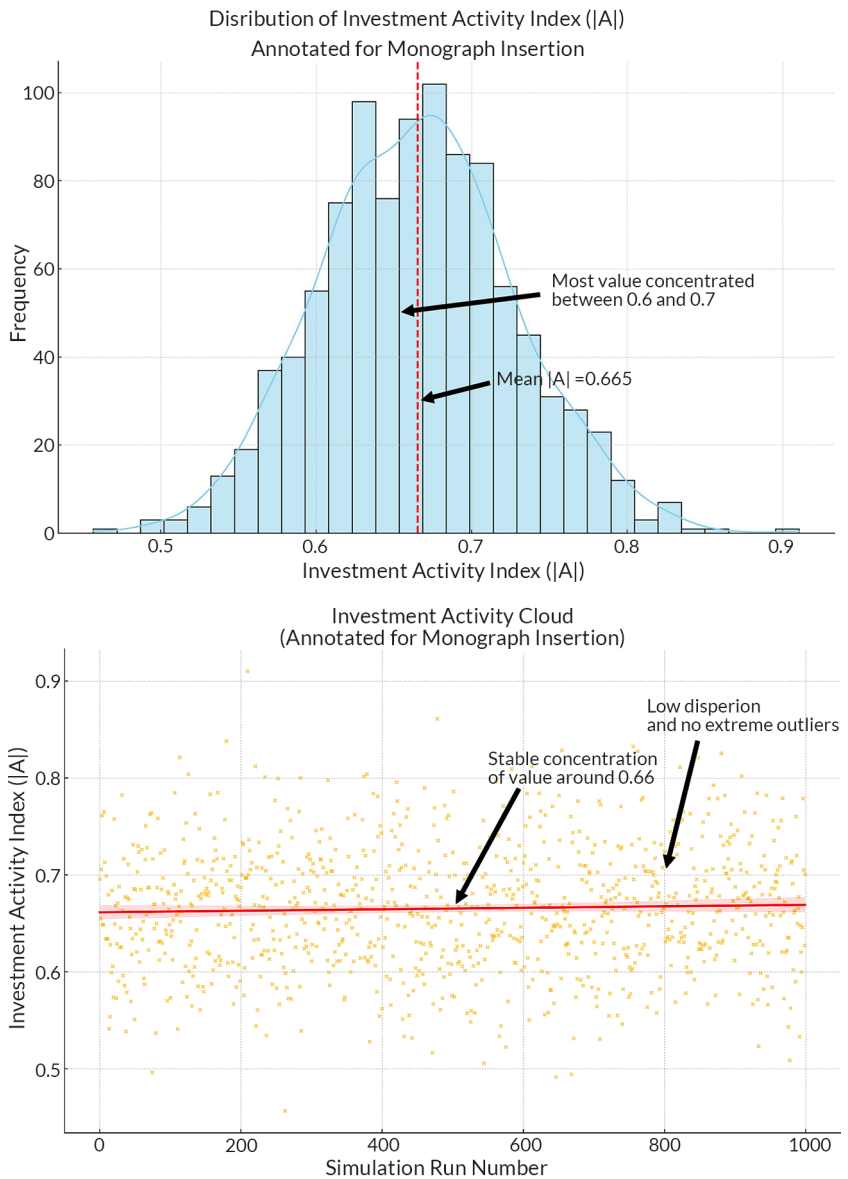


Fig. 4.8 Simulated investment activity landscape: density and dispersion patterns

The results of the conducted simulation confirm that the integration of blockchain technologies and smart contracts into the remediation and revitalization processes can significantly enhance investment activity (including international investment) during the post-war recovery of Ukraine. These findings support the thesis that digital transparency and automation are key factors for attracting capital and strengthening investor trust.

4.6 Conclusion

The conducted research has demonstrated that the implementation of blockchain technologies and smart contracts can serve as a powerful driver of international investment activity in Ukraine, which is undergoing a post-war recovery period. Transparency, trust, and efficiency, ensured by blockchain, address the key problems that have traditionally restrained the inflow of foreign investments – primarily, corruption risks and the lack of guarantees for the targeted use of funds. The analysis of the genesis and potential of blockchain has shown that this technology is mature for widespread application: its advantages in the form of an immutable ledger and automated contracts are recognized worldwide and confirmed by successful cases in both the public and private sectors. Ukraine finds itself in a unique position, where the urgent need for recovery coincides with the readiness of society and the state for digital transformations. A high level of digitalization and the experience of wartime use of crypto technologies have created favorable ground for the implementation of blockchain solutions. The international community, in turn, is interested in ensuring that every dollar provided to Ukraine is used as efficiently as possible – and therefore the openness of a blockchain platform will resonate with partners and donors. The project model of the blockchain system for recovery management developed in this work has concretized exactly how the principles of transparency can be implemented "in hardware and code": through a public project registry, smart contracts tracking the execution of works, asset tokenization to attract grassroots investments, and the direct involvement of citizens. The platform SIBReS, developed by the authors, represents a digital bridge between remediation, revitalization, and investments, combining technological efficiency, social justice, financial transparency, and adaptive management, exemplified through a specific territory, with the potential for successful scalability. It is capable of becoming the core of the digital management system for the country's post-war recovery process. From the perspective of international investors, the proposed model significantly reduces entry risks into the Ukrainian market, while ensuring an unprecedented level of

control and transparency, thereby offsetting traditional concerns related to jurisdiction. Within the framework of the research, a Python simulation with 1,000 runs was conducted and an investment activity cloud was constructed to objectively assess the resilience and variability of investment activity when applying blockchain technologies and smart contracts. The obtained results confirmed that these solutions can significantly reduce investment risks, strengthen trust, and contribute to the stabilization of international capital inflows. The investment cloud clearly demonstrated that the use of innovative technologies serves as an important driver for enhancing transparency and efficiency in the recovery of affected territories, which is particularly crucial for eliminating crisis phenomena and could be relevant for other countries (e.g., in cases of disaster recovery, natural catastrophes, technological accidents, etc.). Moreover, the creation of such a system effectively sets a new standard of investment openness, capable of attracting not only funds for recovery but also direct investments into related sectors such as IT, fintech, and consulting. In other words, blockchain can become part of the brand of the new Ukraine – a country striving to overcome corruption through progressive technologies and to become an attractive and reliable place for doing business.

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CHAPTER 5

Innovative technologies and digital models in the post-war recovery of the transport and logistics system of Ukraine

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Abstract

The presented monographic study is devoted to the study of the role and significance of innovative digital technologies in the post-war recovery of Ukraine's transport and logistics system. It is noted that large-scale destruction in the transport and logistics sector as a result of the war requires not just restoration, but substantial modernization, the foundation of which must be laid on modern digital solutions and technologies. In the scientific work of the authors, morphogenesis, assessment of the current state of the transport and logistics system, as well as the corresponding infrastructure of Ukraine, has been carried out. An in-depth analysis of the prerequisites for digitalization has been conducted – including the aspiration for integration with the EU and global technological trends – and an assessment of the current level of digital development of the national transport and logistics sector is given. The work presents a comparison of Ukraine's positions in international rankings of transport and logistics digitalization with global and regional leaders. The best global practices (Europe, USA, China, etc.) regarding the implementation of digital technologies – from IoT and Big Data to unmanned systems – are considered, and the possibility of their adaptation in Ukraine is assessed. For forecasting the implementation of digital innovations, non-traditional but objective methods are used, namely Porter's Diamond Model of competitive advantages, and a simulation model of technology diffusion based on the S-curve (logistic function), which is often used in innovation theory, has been applied. As a result, practical recommendations are formulated for a "digital reboot" of Ukraine's transport and logistics system in the context of post-war recovery, consisting of a comprehensive

approach to using all the advantages of a convenient geographical location, the actually existing potential of the transport and logistics system, and the promising opportunities that open up with the implementation of advanced digital technologies.

Keywords

Post-war recovery, congruent development, transport and logistics system, digitalization, economic diagnostics, managerial decisions, forecasting, benchmarking, remediation.

5.1 Introduction

The war on the territory of Ukraine caused unprecedented destruction of transport and logistics infrastructure, which set before the country the task of its restoration in the shortest possible time [1]. After the destruction of airports (including Hostomel, Kharkiv, Mykolaiv, Zaporizhzhia) and the blockade or critical damage and disabling of key seaports (Mariupol, Berdiansk, Yuzhny, Kherson), logistics is effectively paralyzed. The destruction of more than 80 sea and river vessels, as well as dozens of airplanes and helicopters, has further aggravated the situation. The railway sector, remaining critically important for military transportation and evacuation, has suffered massive destruction: more than 120 stations and terminals have been damaged, locomotive depots destroyed, and thousands of wagons and locomotives disabled. The total cost of damage to the railway sector reaches 6.5 billion USD, not including hidden costs of logistical delays. Thus, by total losses, Ukraine's transport and logistics system has lost over 56 billion USD, which requires a systemic strategy of remediation, modernization, and re-equipment of all types of transport [2, 3].

All these facts indicate that post-war recovery to the level of "as it was" will be insufficient, as qualitative modernization of the country's transport and logistics system (TLS) is critically needed, taking into account modern technologies and global development trends. It should be acknowledged that the war simultaneously accelerated a number of processes. First, the need to increase the resilience and efficiency of logistics in crisis conditions has intensified. Second, Ukraine's integration aspirations into the European space have become more active, which requires large-scale alignment of transport and logistics with European standards. In particular, Ukraine must implement the norms of the *acquis communautaire* in the transport sector, integrate into the TEN-T network, and ensure long-term connectivity with the transport system of Europe [4]. Third, in recent years Ukraine has established itself as a digital reformer, and this momentum must be maximally expanded and utilized. This refers primarily to the creation of the Ministry of Digital Transformation in 2020 and the launch of the "Diia" application for

the provision of public services online. In the transport and logistics sphere, an important role was played by the "Shliakh" systems (electronic permit for carriers), as well as e-TTN – electronic consignment note, the implementation of which began in 2021. These tools laid the foundation for the digitalization of logistics, and therefore, the post-war recovery must use the accumulated potential to create a sustainable, transparent, and competitive transport and logistics system with corresponding infrastructure [5].

According to the authors' conviction, the expansion and multiplication of the digitalization potential, especially in the transport and logistics sector, can become a driver of economic recovery and Ukraine's integration into international transport corridors. It can and should be understood not only as an infrastructural necessity, but also as a multifunctional accelerator of territorial recovery and revitalization of the national socio-economic system. Moreover, the domestic transport and logistics system can act as a systemic transmission mechanism of economic activity, analogous to the circulatory system of an organism, providing the connection between production potential, consumer centers, and external markets.

Taking into account Ukraine's favorable geographical position at the intersection of East-West and North-South trade routes, even under conditions of limited internal production activity and even at early stages of the recovery process, transit capacities can generate revenues for the state and local budgets. This is especially critical against the background of the shortage of public resources and the urgent need to restore overall fiscal stability. However, it should be recognized that achieving a multiplicative effect from the functioning of the transport and logistics system is possible only under the condition of its prompt restoration to a competitive level, that is, taking into account the requirements of digitalization of logistics chains and the corresponding transport infrastructure.

Thus, the digitalization of the transport and logistics system must become a strategic priority, as it is not only capable of ensuring a rapid economic return on invested resources, but can also create the prerequisites for sustainable development and effective inclusion of Ukraine into global supply chains. This thesis determines the purpose and scope of this monographic study.

5.2 Prerequisites and conditions for the development of digitalization in the transport and logistics system: theoretical, methodological, and practical aspects

One of the significant stages of successful digitalization in the post-war recovery of the transport and logistics system (TLS) is a deep and comprehensive analysis of

the prerequisites and conditions that will largely determine the realism, sustainability, and effectiveness of future development scenarios. According to the authors' conviction, it is an undeniable fact that without understanding the starting point of the current state of development and existing systemic deficits, it is impossible to construct a digital model capable of implementing not only recovery, but also transformational objectives [5, 6].

The scientific exploration conducted by the authors of the monograph made it possible to identify a number of critically important theoretical, methodological, and practical prerequisites that form the objective necessity of digitalization and simultaneously create unique "windows of opportunity" for the introduction of innovative approaches. The key among them are:

1. *The scale of destruction and the need for "congruent" recovery.* The scenario that will ultimately be selected within this study as the most optimal among all possible options is based on the concept of *congruent development* – that is, a strategic choice that is maximally aligned with the current level of available resources, institutional maturity, as well as logistical constraints and external environmental factors. The term "*congruence*" in this context is borrowed from systems theory and management, and denotes a state of structural and functional alignment between a system and its environment. This approach stands in contrast to the formal replication of foreign digital strategies that are not adapted to the realities of the post-war Ukrainian context.

It is especially important to emphasize that the scale of destruction of Ukraine's transport, logistics, and warehousing infrastructure, caused by the full-scale military aggression, is so extensive in nature and magnitude that in a number of regions, post-war recovery will proceed not through modernization, but rather through a complete rethinking and reconstruction from scratch (Fig. 5.1).



Fig. 5.1 Congruent model of digitalization of Ukraine's TLS (transport and logistics system)

This provides Ukraine with a unique opportunity – to implement the principle of build back better, with an emphasis on the introduction of digital innovations based on sustainable architecture. That is, it is not just about technical reconstruction, repair, and restoration of the structural components of the transport and logistics system, but about a complete strategic restructuring on the principles of digitalization.

The above-mentioned principle Build Back Better (BBB) fits perfectly into the strategic priorities of post-war recovery of our country. Its literal translation means "to rebuild better than it was". This principle was first formulated in 2005 after the devastating tsunami in the Indian Ocean and since then has become the basis for recovery programs after natural disasters and catastrophes of various kinds, including UN initiatives and national strategies of different countries of the world that faced the need to eliminate their consequences.

Justifying its scientific significance, it should be formulated as a principle that represents a strategic approach to recovery after emergency events of various nature and scale (including military conflicts), aimed at reducing vulnerability and increasing the resilience of the territorial socio-economic system. In the context of restoring Ukraine's transport and logistics system after the destruction caused by the consequences of military actions, the BBB principle implies not merely the restoration of the former infrastructure, but its modernization taking into account modern technologies and standards. First and foremost, this includes the integration of digital solutions, sustainable and energy-efficient technologies, as well as the improvement of institutional management mechanisms (Fig. 5.2).

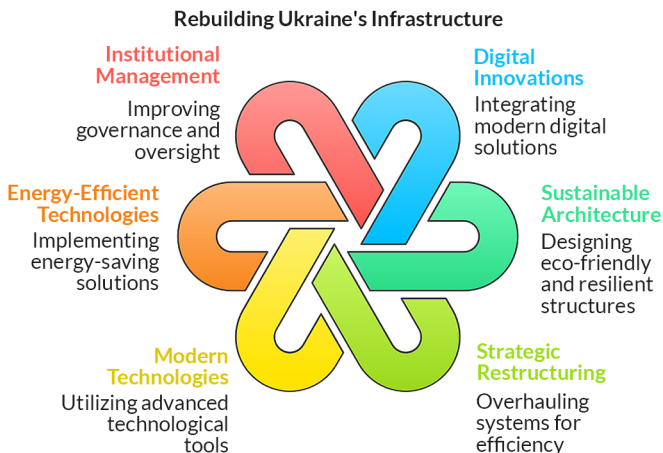


Fig. 5.2 Rebuilding Ukraine's infrastructure based on the build back better (BBB) principle

2. *The imperative of increasing efficiency and resilience: lessons from the vulnerability of transport routes and logistics chains.* Against the background of destruction caused by the war, the imperative of increasing the efficiency and resilience of logistics infrastructure becomes especially relevant. Thus, while the scale and nature of the recorded destruction form the objective necessity for a complete rethinking of infrastructure solutions (this refers to Precondition 1), the second systemic challenge is the exposure of deep-rooted weaknesses in the architecture of logistics chains, many of which existed long before the beginning of the full-scale invasion but were critically exacerbated under the current crisis conditions (Fig. 5.3).

In Fig. 5.4, two pie charts are presented, which allow for a visual assessment of how much the potential of Ukraine's transport and logistics system has decreased as a result of the war.

As is seen, the former multi-vector structure of the TLS has been distorted, which necessitates a strategic revision of national policy. Priority should be given to the restoration of key links: multimodal logistics, port recovery, warehouse modernization, as well as the relaunch and revival of the aviation sector. These steps will be critically important for economic recovery, strengthening export potential, and integration into the EU transport and logistics system.

It must be acknowledged that even before the war, Ukraine's transport sector suffered from chronic underfunding and outdated technologies, which significantly hindered economic activity. More than two-thirds of the infrastructure was morally and physically obsolete since Soviet times. In this regard, along with the renewal of the vehicle fleet and infrastructure facilities, digitalization is considered a chance to eliminate weak points: IoT solutions and sensors will allow real-time tracking of cargo and transport, identifying delays; Big Data and analytical platforms – to optimize routes and vehicle load; predictive analytics systems – to prevent breakdowns and minimize delays. It is an undeniable fact that digital technologies can significantly increase logistics efficiency, reduce fuel and time losses, which is critical for rapid economic recovery.

Moreover, it must be noted that Ukraine's digital infrastructure proved to be a rather resilient and stable structure during the war. All of the above strengthens the argument in favor of maximum digitalization of transport and logistics processes in the near future.

The link between efficiency and resilience becomes a determining factor in choosing the direction of digitalization. In this context, digitalization is no longer seen as a technological option but as a systemic tool for risk management, increased flexibility, and ensuring long-term logistics stability.

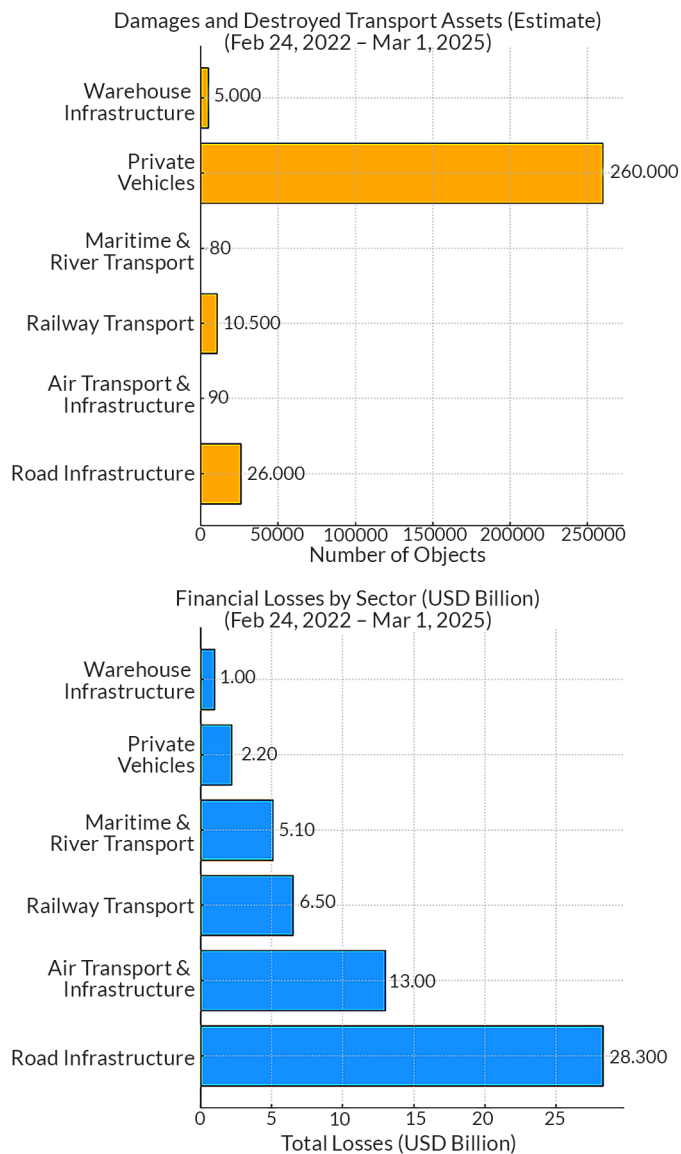


Fig. 5.3 Generalized assessment of damage and destruction to Ukraine's TLS caused by military activity

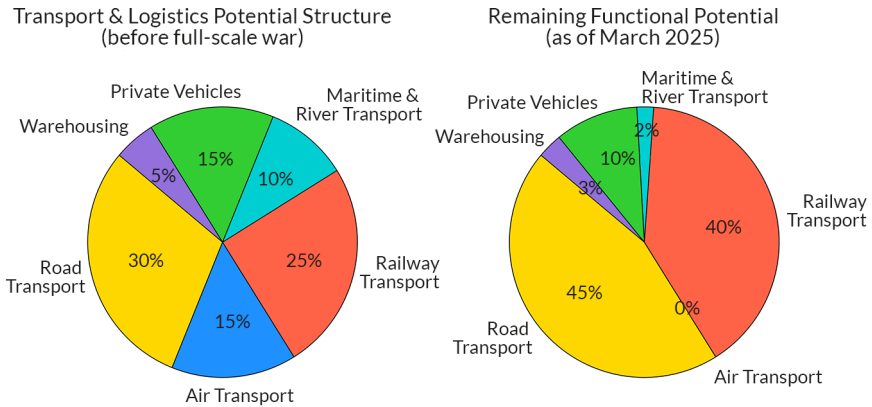


Fig. 5.4 Generalized structure of Ukraine's TLS before military actions and at present

3. *Vector of EU integration and regulatory incentives.* As previously mentioned, the development vector toward EU membership creates a strong impetus for digital transformation. The point is that, in this context, Ukraine is obliged to implement European standards in transport and logistics, many of which are linked to digitalization. For example, starting in 2025, the EU Regulation 2020/1056 on electronic freight transport information (eFTI) comes into force, requiring EU Member States to accept electronic transport documents and data. Ukraine, aiming to integrate into the single market, must harmonize its digital systems with neighboring countries – in particular, to implement electronic consignment notes (e-CMR/e-CN) and unified digital customs solutions compatible with European ones [4]. In the context of the above, it is already strategically important to pay special attention to optimizing the functioning of digital services at border crossings, including automation of passage, synchronization of data with customs services of other countries, and so on.

The published National Transport Development Strategy until 2030, updated by the government, reflects the priority of digital transformation of logistics as one of the key goals of recovery [7]. Thus, within the framework of alignment with the EU, roadmaps are being developed that include digitalization as a necessary condition for integration (including data exchange on cargo flows, compatible information systems, etc.). As is seen, the legal framework is gradually being brought in line with the requirements set by the European Union, and all this creates institutional prerequisites for the successful digitalization of the sector.

4. *The presence of strong domestic IT potential in Ukraine and society's readiness for digitalization.* The Ukrainian IT sector is one of the most developed in Eastern Europe.

The total number of IT specialists in Ukraine is estimated at 346,200 people working in 2,150 companies [8]. Significant domestic IT potential is confirmed by the fact that Ukraine ranks first in Europe in the number of developers [9]. In March 2025, IT service exports reached 598 million USD, which is 15% more than in March 2022 [10].

Ukrainian society also demonstrates a high level of readiness for digitalization, which is confirmed by the following key indicators. At the beginning of 2023, there were 28.57 million internet users in Ukraine, which accounts for 79.2% of the total population [11]. Around 78% of Ukrainians use the internet daily, and 55% of citizens used at least one electronic government service over the past year, for example, through the "Diia" application [12]. It should be noted that the "Diia" platform. Digital Education" helped almost 2 million Ukrainians improve their level of digital literacy. According to published data, Ukraine ranked 5th in the level of development of digital public services and 1st in the E-Participation indicator, which reflects citizens' readiness to participate in government processes through online platforms [13].

Thus, the digitalization of Ukraine's transport and logistics system is unfolding not only as a forced adaptation to destruction, but also as a reflection of a broader convergence dynamic. In essence, a unique point of intersection is forming – a convergence between challenges and opportunities: the destroyed infrastructure requires not just restoration, but the implementation of innovative models, while the level of digital maturity of the population, the availability of IT professionals, and political support create a favorable environment for a "leapfrogging" renewal. This situation fully corresponds to the logic of technological convergence, within which post-crisis societies can adopt and implement advanced solutions more rapidly, bypassing lengthy stages of evolutionary buildup.

The application of convergence theory in this study, according to the authors, makes it possible to more deeply interpret the uniqueness of the current historical moment. This theory explains why Ukraine, despite large-scale destruction and systemic challenges, possesses real potential for accelerated digital development and convergence with advanced models of logistics and infrastructure modernization (**Fig. 5.5**).

Convergence in this context is understood as a strategic "rapprochement" between the objective need for recovery, the internal digital readiness of society, and external institutional support. It is precisely this rapprochement that creates real opportunities for a breakthrough, rather than an inertial scenario of TLS recovery, within which Ukraine can not only catch up but, in many aspects, even surpass traditional development trajectories through the implementation of advanced digital technologies in transport and logistics, as well as in the service sector as a whole.

Thus, the theory of convergence lends the study not only theoretical depth but also allows the explanation of a paradox: destruction becomes a logical impetus for

renewal, and a crisis situation – an entry point for large-scale digital modernization synchronized with European standards. This makes the concept of convergence not merely theoretical but a methodological foundation for the strategic planning of Ukraine's digital recovery.

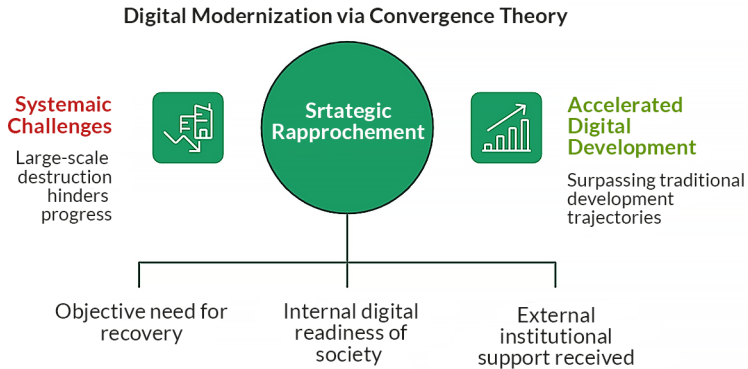


Fig. 5.5 Convergence theory in the context of digitalization of Ukraine's TLS

Further in the study, the current achievements and challenges in the digital development of Ukraine's TLS are examined, as well as how advanced global experience can be applied to overcome existing gaps.

5.3 Analytical assessment of the current state of digital development of Ukraine's transport and logistics system

Before planning the implementation of innovations, it is necessary to objectively assess the current level of digitalization of Ukraine's transport and logistics system, identify strengths and weaknesses, as well as the country's position relative to others. Below is an analytical overview of the state of Ukraine's TLS in terms of digital development at the end of the 2020s (namely, the period after the pandemic and before the start of military actions) [14].

Infrastructure and basic digital services. In terms of basic ICT infrastructure, Ukraine has a relatively good level, characterized by the following: high mobile network coverage (it should be noted that 3G/4G coverage was widespread even in rural areas before the start of military actions), a growing fiber-optic network, and fairly broad popularity of digital services among the population. In addition, as previously noted

in the study, Ukraine was rapidly developing in the direction of digitalizing the public service sector. All these achievements are important and significant for the transport and logistics sphere. For example, digital driver's licenses and vehicle registration documents in the "Diia" application simplify verification processes.

At the same time, it should be acknowledged that specialized digital solutions within Ukraine's TLS are unevenly developed.

Analysis of digital development in railway transport. The state-owned Ukrzaliznytsia (JSC "Ukrzaliznytsia") had certain digitalization elements even before the war, namely: online ticket sales for passengers, a GPS monitoring system for some locomotives and wagons, and electronic document flow for freight transportation. However, the level of process automation remained low. For example, to characterize the situation overall, it should be noted that train traffic management systems on many routes were outdated and in need of modernization to the standards of the European Rail Traffic Management System (ERTMS), and the accounting of freight wagons was often maintained in fragmented databases [15].

At the same time, international projects began to pave the way for the step-by-step development of digitalization in railway transport. For example, in 2020, Ukrzaliznytsia joined a pilot project for the implementation of the CIM/SMGS electronic consignment note for transit shipments, and in 2021 launched a mobile application for customers to track shipments. These steps, although selective, demonstrated the potential for digitalization.

After 2022, Ukrzaliznytsia was forced to become more flexible: digital passes were introduced for evacuation trains, and a freight wagon coordination system was created in real time for exports through western border crossings (referring to exports under the "Solidarity Lanes"). Nevertheless, an integrated digital system in the railway sector does not yet exist – it is under development and is expected to be implemented during the reform of Ukrzaliznytsia. One positive factor in this direction is that in March 2025, the Supreme Council introduced the Railway Transport Law, which provides for market liberalization and the stimulation of private investment [4]. In the analytical note attached to it, special attention is focused on the need to update the railway's IT systems alongside reforms of its structure. Fundamental reforms in this direction, in the authors' view, could open new opportunities for building the digital infrastructure of the TLS (including the creation of a unified digital dispatch center, a unified information system for freight transport, etc.).

Analysis of digital development in road transport. It should be immediately noted that the state of digital development in Ukrainian road transport has historically been characterized as more fragmented, primarily due to the large number of private carriers and the absence of a unified strategy. Digital initiatives were implemented in

a scattered manner, without coordination among various industry participants. However, it is worth highlighting the digital innovations that were introduced, namely, the Weight-in-Motion (WiM) system on major highways (referring to automatic weight control for trucks), as well as the electronic truck border queue system "eCherha", which was launched in 2021 [16, 17].

However, other aspects of digitalization lagged behind: for example, the electronic tolling system had only just started operating, onboard computers and telematics were not used by all companies, and data exchange on cargo between road carriers and other types of transport was quite weak.

After the war began (since 2022), accelerated transformation started to occur under the pressure of circumstances. The importance of road transport increased significantly (primarily in the context of the strategic role of road transport for humanitarian and military logistics), which stimulated rather substantial digital changes. In 2022–2023, the government began actively promoting TIR-EPD – electronic pre-declaration to simplify border crossing – and also announced the complete digitalization of the permit system for freight carriers by 2025 [18]. Large logistics companies themselves began implementing TMS (Transportation Management Systems) and tracking systems. For example, one of the largest private postal and logistics operators – Nova Poshta – received a 13 million EUR investment from the EBRD in 2021 for the automation of a sorting center and the implementation of a smart parcel logistics management system [19].

This project made it possible to double the sorting capacity and improve the efficiency of road transport use. It serves as an example of successful digitalization at the business level. However, small and medium-sized logistics firms (small and medium-sized enterprises (SMEs) make up more than 90% of logistics companies in Ukraine – these are small carriers, freight forwarders, warehouse operators who often work locally or as subcontractors for large operators) significantly lag behind [20].

According to the OECD (Organization for Economic Co-operation and Development), Ukrainian SMEs:

- weakly apply ERP, TMS, WMS, analytical and monitoring platforms;
- practically do not use AI, IoT, or eFTI (electronic freight transport information exchange);
- rarely invest in cybersecurity and the digital competencies of their personnel [21].

Thus, the war became a catalyst for the accelerated digital transformation of road transport in Ukraine, forcing industry participants to quickly adapt to new realities and seek effective solutions in crisis conditions.

Analysis of the digital development of maritime and river transport. It should be noted that before the full-scale war, digitalization of maritime and river transport in Ukraine was at an early stage, requiring a systematic approach and coordination of efforts by all interested parties. Digital initiatives were implemented in a fragmented way, without coordination among different stakeholders in the sector. For instance, in the port of Odesa, a Port Community System (PCS) was in operation for data exchange between terminals, the port administration, and customs authorities [22].

However, the level of integration was lower than in the world's leading ports. Between 2019 and 2021, digitalization of vessel call documentation processes began (including the electronic ship declaration). In river ports of the Danube region, digitalization was minimal.

The war and blockade of the country's seaports forced a reorientation toward the Danube. Thus, in the ports of Izmail and Reni, cargo flow management tools began to be widely implemented, and work on electronic data exchange with Romanian ports was actively pursued (including via the Danube Commission). The reorientation of Ukrainian exports to Izmail, Reni, and Ust-Dunaisk, in the authors' view, may become an impetus for the post-war revival of river transport. In this regard, the Ministry of Infrastructure announced plans to equip these ports with electronic document management systems and digital vessel traffic monitoring systems alongside the physical reconstruction of berths. International partners (including the Danubius Ports Administration from the EU) are ready to share software solutions with the Ukrainian side. Thus, the post-war restoration of ports is seen as a chance to immediately build "smart ports" with full digital coordination of vessel flows, cargo, and customs procedures.

It should be separately noted that the authors of this monograph have deliberately not analyzed the level of development of air transport, as it is currently completely paralyzed. The next strategically important aspect, which currently plays an extremely vital role, is customs and border logistics.

It is worth emphasizing that the digitalization of transport and logistics processes at the border is a critical element for Ukraine, considering the reorientation to EU land corridors. Even before the full-scale military actions began, Ukraine started implementing NCTS (an IT system designed to provide better management and control of goods within the framework of) its accession to the Common Transit Convention and experimented with electronic data exchange with Poland and other neighboring countries.

On October 1, 2022, Ukraine officially became the 36th participant of the Convention, which enabled Ukrainian companies to use simplified procedures for moving goods between member countries using a single electronic transit declaration and guarantee.

In 2023, Ukraine continued the digitalization of customs procedures by implementing Phase 5 of NCTS. This allowed businesses to use the latest version of the system, providing more efficient electronic data exchange and reducing customs clearance time. Ukraine became one of the first countries to implement NCTS Phase 5, despite the difficult conditions caused by the war [23, 24].

The eCherha electronic queue system was also introduced, significantly simplifying border crossing for freight transport, especially under wartime conditions and the growth of export flows. As of May 2025, eCherha operates at 23 international border checkpoints for trucks and 28 checkpoints for buses, covering borders with Poland, Romania, Hungary, Slovakia, and Moldova. In March 2025, the system was expanded to include trucks weighing from 3.5 tons, which allowed a greater number of carriers to be covered and increased the efficiency of border crossings [25].

Since its launch in 2022, more than 1.5 million border crossings have been registered through the system, 1.3 million of which were trucks.

The Ukrainian government plans further expansion and improvement of the eCherha system, including:

- integration with European data exchange systems, in particular ensuring automated exchange of information between Ukrainian and European customs authorities;
- implementation of peak load forecasting, in the context of developing mechanisms for predicting and managing peak loads at checkpoints;
- expansion of functionality, namely adding new features and capabilities to the system based on user feedback.

Thus, eCherha has become an important tool in the digitalization and modernization of Ukraine's border logistics, contributing to improved efficiency and transparency of border crossing processes.

Alongside this, within the framework of the EU-supported digital recovery program, it is planned to create a "unified data exchange system at the border" – a kind of digital corridor where declaration, certification, and permit data will be automatically transferred between the Ukrainian and European sides. This is a large-scale project, but its implementation will give Ukraine a qualitative leap in logistics efficiency at its borders. As the experience of the war has shown, the bottlenecks were the human factor and paper-based procedures at crossings; their digitalization is a matter of the competitiveness of Ukrainian exports.

It can be confidently stated that the creation of a unified data exchange system at the border is a key step toward Ukraine's integration into the European customs space. This project not only increases the efficiency of customs procedures but also contributes to strengthening economic ties with the EU, which is especially important in the context of the country's post-war recovery.

Level of digitalization: international indicators. Although a direct metric for "logistics digitalization" is absent in international statistics, indirect indicators and rankings allow an assessment of Ukraine's position relative to other countries. According to the World Bank's 2023 report, Ukraine ranked 92nd out of 139 countries in the Logistics Performance Index (LPI) with an aggregate score of 2.7 out of 5. This indicates a significant decline compared to 2018, when Ukraine held the 66th position with a score of 2.83. For comparison, Poland ranked 28th in 2023 with a score of 3.5, and Germany ranked 3rd with a score of 4.1. This highlights the lag of Ukraine's TLS in the development of logistics infrastructure and processes.

The analytical assessment of Ukraine's LPI in 2023, broken down by six components [26], is as follows:

- efficiency of customs procedures: score – 2.3;
- quality of infrastructure: score – 2.4;
- international shipments: score – 2.5;
- logistics competence: score – 2.6;
- tracking and tracing: score – 2.5;
- timeliness of delivery: score – 2.8.

The above data indicate the need for comprehensive improvement of Ukraine's TLS, including customs clearance procedures, infrastructure development, and the implementation of modern technologies for cargo tracking.

5.4 Benchmarks of global best practices and opportunities for their adaptation in Ukraine.

For the successful digital transformation of Ukraine's TLS, it will be useful to orient toward global best practices. Below are examples of innovative digital technologies and models implemented in different countries and companies, which can serve as benchmarks for further adaptation and implementation. Special emphasis is placed on those solutions that have proven effective and are potentially applicable under Ukrainian conditions. According to the authors, a deep analysis of positive international practice – especially in the context of digitalization – is critically important for the successful and fundamental transformation of Ukraine's transport and logistics system aimed at increasing its competitiveness:

1. *"Digital Freight Train" (France).* The state-owned railway company SNCF in France is implementing the Train Fret Digital program – "Digital Freight Train" This is a comprehensive digital solution that includes equipping wagons and locomotives with IoT sensors, as well as using automated systems for transport planning and

monitoring. As a result, SNCF can monitor trains in real time, optimize train composition and scheduling, thereby improving efficiency and reducing costs [1].

An additional effect is achieved – the reduction of CO₂ emissions through more rational use of railway transport instead of road transport. The results of this program demonstrate not only ecological impact but also market share growth. For example, despite structural changes in Fret SNCF, in the first half of 2024, the Rail Logistics Europe division increased its revenue by 9.5%, reaching 17 million EUR, and profitability (EBITDA) grew to 91 million EUR compared to 28 million EUR in the same period of the previous year [27].

According to the authors of this monograph, it would be reasonable to adapt and implement a similar project for Ukraine, specifically during the restoration of railway communication – especially along international corridors – by integrating such a program into Ukrzaliznytsia (UZ). For example, in a pilot project on the European 1435 mm gauge in the Lviv region, it would be possible to immediately introduce digital freight train management, integrated with European dispatch centers. This would help effectively utilize new opportunities for access to TEN-T and eliminate "bottle-necks" at border crossing points through schedule synchronization and load balancing.

2. *Green last mile logistics (Germany)*. The "Green Last Mile Logistics" project, implemented in Germany, is a strategic initiative aimed at significantly reducing CO₂ emissions in urban centers through the introduction of sustainable logistics solutions (this refers to the transition to environmentally friendly vehicles such as electric trucks and e-bikes for deliveries in city centers).

One of the most prominent examples is the Emission-Free Delivery model implemented by DACHSER. In 2025, the company plans to double the number of cities covered by the Emission-Free Delivery program – from 12 to 24, including Amsterdam, Barcelona, Dublin, Hamburg, Cologne, London, Malaga, Rotterdam, Stockholm, Toulouse, Warsaw, and Vienna [28].

This approach has already proven its effectiveness and can be adapted to Ukrainian conditions, especially in the post-war recovery of cities and logistics infrastructure. The implementation of the "Green Last Mile Logistics" concept in Ukraine could become an important step toward sustainable development and integration into the European logistics space.

3. *AI for forecasting and optimization of logistics operations*. Leading global logistics companies actively use artificial intelligence (AI) in transport and logistics systems. For example, DHL (Germany) uses AI for predictive maintenance, warehouse automation, and real-time data analysis. DHL's AI algorithms optimize delivery routes, predict delays, manage warehouse inventory, and improve customer service through chatbots.

As part of e-fulfillment process optimization, DHL developed IDEA software, which uses AI algorithms to optimize order picking routes and task distribution among warehouse staff. The results are impressive:

- up to 50% reduction in walking distances for workers;
- up to 30% increase in warehouse productivity;
- decreased error rates and training time for new staff [29].

In addition, DHL has introduced sorting robots capable of handling 1,000 + parcels per hour with 99% accuracy, boosting sorting center throughput by 40% [30].

UPS (USA) implemented the ORION system, which uses machine learning to determine the optimal delivery routes for each courier, saving the company millions of liters of fuel. Since its launch in 2012, UPS has achieved:

- route reductions of 6–8 miles/day per driver, equaling 100 million miles/year;
- up to 10 million gallons of fuel saved annually;
- ~100,000 metric tons of CO₂ emissions reduced/year;
- 300–400 million USD saved per year.

In 2021, UPS introduced Dynamic ORION, enabling real-time routing adjustments based on road conditions and new delivery requests (including backloads and combined deliveries), reducing routes by an additional 2–4 miles/day per driver [31].

Adapting similar solutions in Ukraine could reduce costs, lower environmental impact, and improve customer service quality. According to the authors, the UPS ORION experience could be used by Ukrposhta and Nova Poshta for urban deliveries, integrating traffic data from Ukrainian cities.

Maersk, a global leader in ocean container shipping, actively implements Internet of Things (IoT) technologies to improve the efficiency and transparency of logistics processes. One of its key solutions is remote container management (RCM), providing real-time container monitoring [32].

Maersk currently operates around 300,000 smart containers that transmit location, temperature, and condition data in real time. In addition to operational optimization and loss reduction, customer service has significantly improved – customers use the Captain Peter™ platform to access real-time cargo status [33].

The Maersk experience demonstrates the significant advantages of using IoT in logistics, and its adaptation in Ukraine could greatly enhance the efficiency and competitiveness of the national transport system – especially in container shipping.

4. *Warehouse automation and robotics (USA, China).* The company XPO Logistics (USA) is known for implementing robots in its distribution centers: automated sorters and loaders, controlled by a centralized AI system, have significantly accelerated order processing. The company has deployed over 5,000 collaborative robots (cobots) in its warehouses across North America. These robots work alongside

humans, performing tasks such as picking, packing, and sorting goods, thereby increasing both safety and productivity of operations [34].

The use of robotic systems and machine learning technologies has allowed XPO to double its productivity and improve performance by an average of 40% [35].

The Blue Yonder warehouse management system enabled XPO Logistics to achieve 99.9% inventory accuracy for some clients, and also to increase the overall efficiency of warehouse operations [36].

The next benchmark is Cainiao (China) – the logistics arm of Alibaba, which successfully uses robots and drones for deliveries, especially in last-mile rural logistics, and manages freight flows using real-time AI. It can be confidently stated that Cainiao has created some of the most advanced smart warehouses, where almost all operations are automated.

In 2023, the company announced the large-scale deployment of Level 4 autonomous vehicles for parcel delivery on public roads, demonstrating Cainiao's commitment to last-mile delivery automation [37].

During the annual Double 11 (November 11) shopping festival, the company processes billions of parcels through the use of Big Data, artificial intelligence, and machine learning, which significantly accelerates delivery [38].

It is worth noting that drone delivery is rapidly developing in China. Well-known companies such as Meituan and JD Logistics actively use drones and autonomous vehicles to deliver goods, especially in hard-to-reach areas.

In particular, Meituan reported the launch of 53 drone delivery routes in major Chinese cities, completing over 400,000 orders by December 2024 [39, 40].

According to the authors, post-war logistics recovery in Ukraine is a chance to build modern distribution centers in place of outdated warehouses. The application of robotics does not require enormous funds when building from scratch: there are already Ukrainian integrators capable of supplying warehouse conveyors, sorting lines, and more.

Therefore, the highest state authorities should motivate the creation of logistics hubs with a high level of automation (for example, through tax incentives or joint investments with international companies). This is especially relevant for multimodal nodes, which are included in Ukraine's recovery plans [4].

5.5 Forecasting the implementation of digital technologies in Ukraine's TLS

The forecast of digital technology development in the transport and logistics system (TLS) of Ukraine is a complex task due to numerous uncertainties (recovery pace,

volume of investments, external environment). To obtain an objective assessment, this study uses a combination of forecasting methods, namely:

1. The primary method is *Porter's Diamond Model*, which is used as the basic forecasting tool. Within the framework of the forecast analysis, key factors will be evaluated, including: human resources and infrastructure potential, internal demand, related industries, regulatory framework, and external support (EU, USA, etc.).

2. As a complementary method, scenario analysis (3 scenarios) was selected: *optimistic scenario* – active implementation of digital technologies with the support of the EU and investors; *realistic (baseline) scenario* – partial implementation, depending on internal reforms and external investments; *pessimistic scenario* – characterized by slow implementation of digital technologies, as well as minimal interest from economic actors and minimal government support. Within the framework of scenario analysis, a *simulation model of technology diffusion based on the S-curve (logistic function)* was applied.

3. As a third method, the authors selected a *Priority Matrix*. It is precisely the combination of these three approaches that can provide an objective vision of the future prospects for the development of digitalization in Ukraine's TLS.

Priority matrix: assessment of key digitalization directions. To begin with, the authors of the study selected and evaluated the key directions of digitalization (a 1-to-5 scale was used). Evaluation criteria:

- impact on efficiency and competitiveness;
- technological maturity;
- required costs and resources (the higher the costs – the lower the score);
- compliance with EU requirements;
- sustainability and security.

It should be noted that as a basis for assigning scores under each of the criteria, the following sources were used:

- reports by the World Bank and USAID on the digital modernization of customs checkpoints;
- European regulations on eFTI and NCTS, official EU publications on multimodality and IoT;
- analytical research by Logistics Business and logistics trends reports (World Economic Forum);
- official reports by the Ministry of Infrastructure of Ukraine on the status and plans for transport digitalization;
- reports and analytics from the We Build Ukraine platform, and research publications by DAI/USAID (**Table 5.1**).

To enhance the significance of the research, it is proposed to use weighting coefficients (from 1 to 5) for each criterion (**Table 5.2**).

The formula for calculating the final index value (I) was determined as follows

$$I = \sum (R_i \cdot W_i), \quad (5.1)$$

where R_i – score of the criterion (1–5); W_i – weight of the criterion (1–5).

The results of the final indicators calculation are collected in (Table 5.3).

Table 5.1 The overall score-based assessment of key digitalization directions

Digitalization Direction	Effectiveness and competitiveness	Technological maturity	Costs and resources	Compliance with EU requirements	Sustainability and security	Total
1. Border customs digitalization	5	5	4	5	5	24
2. IoT monitoring platforms	5	5	4	5	5	24
3. Multimodal logistics	5	4	3	5	5	22
4. Drones (UAVs)	4	3	2	3	4	16
5. AI/Big Data analytics	5	4	3	4	5	21
6. Blockchain	3	2	2	3	4	14

Table 5.2 Weighting coefficients by criteria

Criterion	Weight coefficient (W)	Justification of weight
Efficiency and competitiveness	5	Key indicator
Technological maturity	4	Important for implementation
Costs and resources	3	Medium value
Compliance with EU requirements	5	Strategically important
Sustainability and security	5	Strategically important

Table 5.3 Calculation of the final indicator – index of key digitalization directions

Direction	Calculation formula	Final score (I)
Border customs	$(5 \times 5) + (5 \times 4) + (4 \times 3) + (5 \times 5) + (5 \times 5) = 104$	104
IoT platforms	$(5 \times 5) + (5 \times 4) + (4 \times 3) + (5 \times 5) + (5 \times 5) = 104$	104
Multimodal logistics	$(5 \times 5) + (4 \times 4) + (3 \times 3) + (5 \times 5) + (5 \times 5) = 98$	98
AI and Big Data	$(5 \times 5) + (4 \times 4) + (3 \times 3) + (4 \times 5) + (5 \times 5) = 94$	94
Drones	$(4 \times 5) + (3 \times 4) + (2 \times 3) + (3 \times 5) + (4 \times 5) = 79$	79
Blockchain	$(3 \times 5) + (2 \times 4) + (2 \times 3) + (3 \times 5) + (4 \times 5) = 69$	69

As can be seen from the table data, the first two key directions of digitalization are the implementation of advanced technologies at border crossing points and the introduction of an IoT platform; in third place is the digitalization of multimodal logistics. Completing the list of digitalization priorities in Ukraine's TLS are the implementation of AI and Big Data, drones, and Blockchain.

The next stage of the study is the analysis of Ukraine's competitive advantages in the digitalization of the transport and logistics system (M. Porter's model). It should be noted that M. Porter's model (Porter's Diamond) allows for an analysis of a country's competitive advantages across four groups of factors: factor conditions, demand conditions, related and supporting industries, and firm strategy, structure, and rivalry. In the context of digitalization of Ukraine's transport and logistics system (TLS), this model helps identify the strengths and weaknesses that influence the success of the digital transformation of transport and logistics. TLS digitalization includes the introduction of information technologies into transportation, warehousing, customs procedures, and other logistics processes to improve efficiency and integration into global supply chains.

Analysis of factor conditions. Factor conditions include, above all, the resources that form the basis of competitiveness. According to the authors, these include: human capital (availability of qualified personnel, especially in IT and engineering), infrastructure (both transport and digital), and the geographical location of the country. **Table 5.4** presents a score-based assessment of the above-mentioned factors. Due to the need for objectivity and the absence of precise data at the time of the study, it was decided to use data starting from the year 2020 as a baseline.

Demand conditions analysis. This component makes it possible to assess how much internal and external demand stimulates innovation and digital development of the TLS. In the Ukrainian context, internal demand is important (referring to the needs of the local market for modern logistics services, including e-commerce), as well as external demand (referring to export-import flows and transit), and regulatory requirements of the EU as a major trade partner and integration direction. **Table 5.5** summarizes the assessment data.

Related and supporting industries. This block analyses the presence of well-developed related industries in the country that can enhance the competitive advantages of the core industry (in our case – transport and logistics). These include, above all, the IT sector (software and service development), telecommunications (communication and internet), the transport industry itself (carriers, warehousing, etc.), as well as donor programs and investments supporting reforms in the TLS sector. **Table 5.6** presents the summarized evaluations.

Table 5.4 Score-based assessment of key factors for evaluating the competitiveness of Ukraine's TLS

Factor conditions	Score	Justification (since 2020)
Human capital	4/5 (High)	A high level of education and a strong IT sector provide Ukraine with personnel for digital transformation. According to the global innovation index (WIPO), in 2023 Ukraine ranked 55th overall, including 54th in human capital and research
Infrastructure	2/5 (Low)	According to the 2023 logistics performance index (LPI) published by the World Bank, Ukraine received the following scores, which confirm the overall assessment: overall LPI index – 2.7 out of 5, indicating a medium level of logistics performance, and the quality of trade and transport infrastructure – 2.4 out of 5, reflecting low infrastructure quality, including roads, railways, and ports. These indicators, in addition to the infrastructure destruction caused by military actions, point to the need for significant investments in the modernization and restoration of the country's transport infrastructure
Geographical location	5/5 (Very High)	Ukraine has a strategic geographical location, confirmed by the following facts: 1) transit corridor between Europe and Asia – Ukraine is part of several international transport corridors, including Pan-European Corridors No. 3, No. 5, No. 7, and No. 9, as well as the TRACECA initiative; 2) the country has access to the Black and Azov Seas; 3) Ukraine ranks 17 th in the world by the length of its railway network, which provides connections between major industrial centers and ports

Source: [41]

Note: the score in the range from 1 to 5 indicates the comparative strength of the factor: 1 – very weak point, 5 – very strong point

Table 5.5 Score-based assessment and description of external and internal demand

Demand Conditions	Score	Justification (since 2020)
Internal demand	3/5 (Medium)	Internal demand in Ukraine remains moderate despite economic challenges related to the war. For example, in 2023, private consumption accounted for 60.7% of nominal GDP, indicating a significant role of internal demand in the country's economy. However, due to ongoing military actions, real GDP data is not currently available in open sources, which led to a medium score
External (export-import) demand	4/5 (High)	Ukraine actively participates in international trade despite current challenges. In 2023, Ukraine's exports amounted to 40.3 billion USD and imports to 55.2 billion USD, reflecting a significant volume of foreign trade. As for trade turnover, in 2024 it increased by 13% compared to 2023, reaching 112.3 billion USD
EU requirements (regulatory demand)	4/5 (High)	The deep and comprehensive free trade area (DCFTA) agreement provides for the gradual harmonization of Ukrainian legislation with EU norms, including technical regulations and standards. Ukraine has adopted more than 30 technical regulations, most of which comply with EU directives, facilitating the export of Ukrainian goods to the European market

Source: [42–44]

Table 5.6 Score-based assessment of related and supporting industries of Ukraine's TLS

Related and supporting industries	Score	Justification (since 2020)
IT sector	5/5 (Bery high)	A strong domestic IT industry is a key driver of TLS digitalization
Telecom infrastructure	4/5 (High)	Developed telecommunications support digital transformation
Transport industry (basic)	3/5 (Medium)	The sector of transport companies and logistics operators in Ukraine shows a mixed level of development. A strong side is the presence of major players covering different segments: Ukrzaliznytsia (the largest railway network), Ukrposhta and private courier services, ports (Odesa, Yuzhny, and others), and tens of thousands of small freight carriers

Strategy of firms, industry structure, and competition. The final component of Porter's Diamond reflects the business environment in which TLS sector companies operate: firms' strategies and initiatives, the structure of the industry, and the level of competition, as well as state policy and the progress of reforms in the sector. This block determines to what extent internal conditions facilitate or hinder digital innovations. **Table 5.7** illustrates the situation.

Below let's present the visualization of Porter's Diamond (**Fig. 5.6**).

Table 5.7 Score-based assessment of TLS firms' strategy, industry structure, and competition

Strategy, industry structure, and competition	Score	Justification (since 2020)
1	2	3
Reforms and deregulation	3/5 (Medium)	Since 2020, Ukraine has carried out a number of important reforms in the transport sector, although many of them are still unfinished
Business initiatives (firm innovation)	4/5 (High)	Ukrainian logistics businesses show flexibility and capacity for innovation, especially in response to crises. Major private companies are investing in IT: Nova Poshta has deployed its own courier IT platform and is even entering EU markets; Agri holdings are implementing grain transportation monitoring systems (GPS trackers on wagons); warehouse networks use Big Data to optimize inventory. Startups are finding applications in logistics: truck-sharing services have emerged, and Ukrainian teams are involved in developing global drone delivery solutions. During the war, businesses independently established alternative logistics chains (e.g., agricultural exports via the Danube) and quickly adapted to new requirements – many exporters mastered European electronic certification and customs systems

Continuation of Table 5.7

1	2	3
Level of competition and industry structure	3/5 (Medium)	The competitive environment in Ukraine's transport and logistics sector is heterogeneous. In some segments, competition is high (road freight, forwarding, warehousing – many players, including foreign ones), which stimulates efficiency. However, other segments are dominated by state monopolies or oligopolies: freight rail transport is almost entirely controlled by Ukrzaliznytsia, monopolistic practices were present in the port sector until recently, and the air transport market is dominated by a limited number of airlines. Insufficient competition has traditionally led to stagnation and weak customer orientation
State policy	3/5 (Medium)	In recent years, the state has shown initiative in digital transformation (creation of the Ministry of Digital Transformation, the "Diia" portal, etc.), which has had a positive impact on the TLS. Government systems have been launched: e-queues at the border, open data from Ukravtodor on road conditions, and online platforms from Ukrzaliznytsia for shippers. The National Transport Strategy until 2030 was adopted, where digitalization is named a priority. In 2023, the government announced its course toward joining the EU digital single market, which implies adapting all digital infrastructure (including logistics) to European standards. However, in the area of direct transport management, problems remain: insufficient funding for infrastructure maintenance, and complex procedures for project coordination between agencies

Radar Chart: Balance of Ukraine's Competitive Factors (Porter's Diamond)

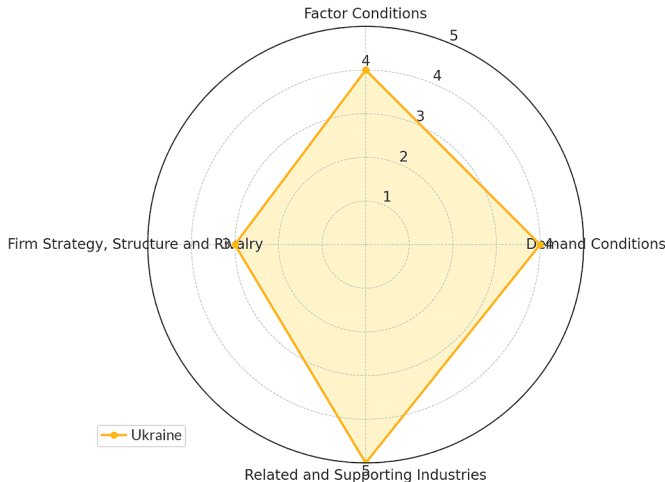


Fig. 5.6 Visualization of the results of competitive advantage analysis
of Ukraine's TLS (Porter's model)

Modelling future development: S-curve of digitalization of Ukraine's transport and logistics system. Based on aggregated data, the authors conducted modelling of digitalization rates using the Python 3.10 programming language and the Matplotlib library for data visualization. The following were also used: the NumPy library for numerical calculations (creation of data arrays, calculation of function values); and the SciPy library (for precise curve visualization – in our case, the basic logistic formula was used).

Model type. As the basic function for forecasting, the logistic function of innovation diffusion (the so-called S-curve, or logistic growth) was applied. The logistic function best describes the dynamics of innovation diffusion, where growth begins slowly, then accelerates (forming an "S" shape), and eventually stabilizes at a certain level of maturity.

The formula used for the modelling

$$y(x) = \frac{L}{1 + \exp(-k \cdot (x - x_0))}, \quad (5.2)$$

where $y(x)$ – the level of digitalization maturity in year x ; L – the maximum maturity value (4.5–5.0); k – the diffusion rate coefficient (0.25–0.5); x_0 – the year of maximum acceleration in innovation diffusion; \exp – exponential function.

Forecasting horizon: 2023–2035.

The forecast graphs of the S-curve of digitalization of Ukraine's TLS are presented below (**Fig. 5.7**).

The model takes into account that the implementation of new technologies proceeds slowly at the initial stage, then accelerates upon reaching a critical mass, and finally reaches a saturation plateau. Calculations showed that under favorable conditions, the inflection point (sharp acceleration of digitalization) for Ukraine may occur in 2027–2030, and saturation – by the beginning of 2034. This quantitative assessment correlates with the optimistic and baseline scenarios, providing additional justification for the forecasts presented above. It is important to emphasize that the proposed forecast is not deterministic, but conditional. Its goal is to indicate what needs to be done to bring reality closer to the optimistic scenario, and what risks to consider in order to avoid the realization of the pessimistic one.

Interpretation of the presented forecast data:

- *optimistic scenario*: rapid acceleration of digitalization is expected, in the best case, after 2026–2027, with maturity reached by 2030;
- *baseline scenario*: moderate growth rates with maturity level ~ 4.7 expected only by 2032;

– *pessimistic scenario*: characterized by "sluggish" digitalization implementation in the transport and logistics sector, with stabilization at the level of 4.5 expected after 2034.

This fully corresponds with the historical analysis of the recovery process in other countries, which restored their transport and logistics systems over a fairly long-time horizon (**Table 5.8**).

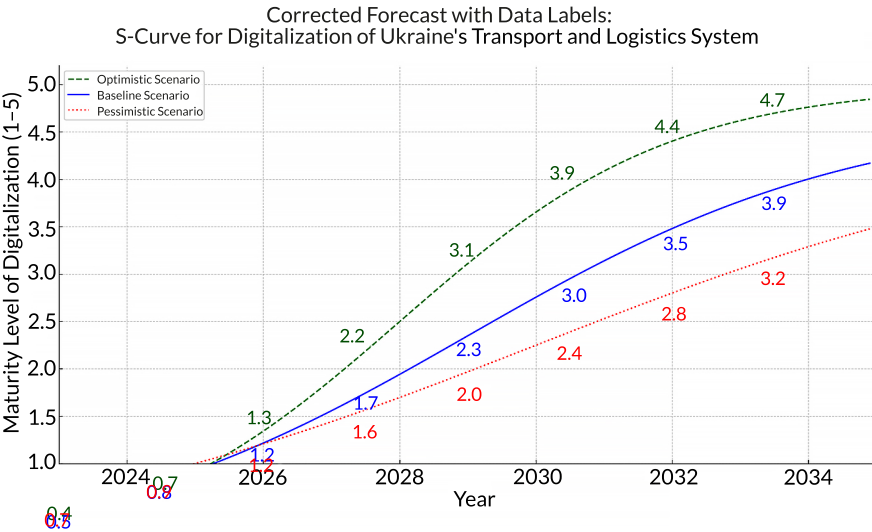


Fig. 5.7 S-Curves of digitalization forecasts for Ukraine's transport and logistics system

Table 5.8 Historical analysis of post-war recovery of the transport and logistics system		
Country	TLS – recovery period	Description
Germany (Post-WWII)	10–15 years (with U.S. coordination under the Marshall Plan)	With massive international assistance
South Korea (1950s)	≈ 15 years	With large-scale U.S. assistance
Bosnia and Herzegovina (1995)	10 + years	Small country, limited resources
Iraq (2003–the present)	15 + years (unfinished)	Political instability hinders recovery

In the opinion of the authors of this study, given that Ukraine is a country with a vast territory and a complex nature of interrelated influencing factors, as well as

due to the large-scale destruction of the TLS during military activity, even under optimistic scenarios, five years will not be sufficient to achieve full digital maturity. In this regard, it will be necessary, after the end of active military operations, to implement a set of remediation measures as the initial stage, which will be able to launch a chain of positive multiplier effects across all sectors and branches of the national socio-economic system, among which the transport and logistics system (TLS) occupies a leading position [45–47].

Finally, the concluding stage, following the economic diagnostics and further forecast modelling, will be the visualization aimed at forming the "Roadmap" of the digitalization of Ukraine's TLS. According to the authors of the study, the most optimal tools that allow for the synthesis of the previously obtained results are the combination of the Layered Timeline + Heatmap Matrix (Fig. 5.8).

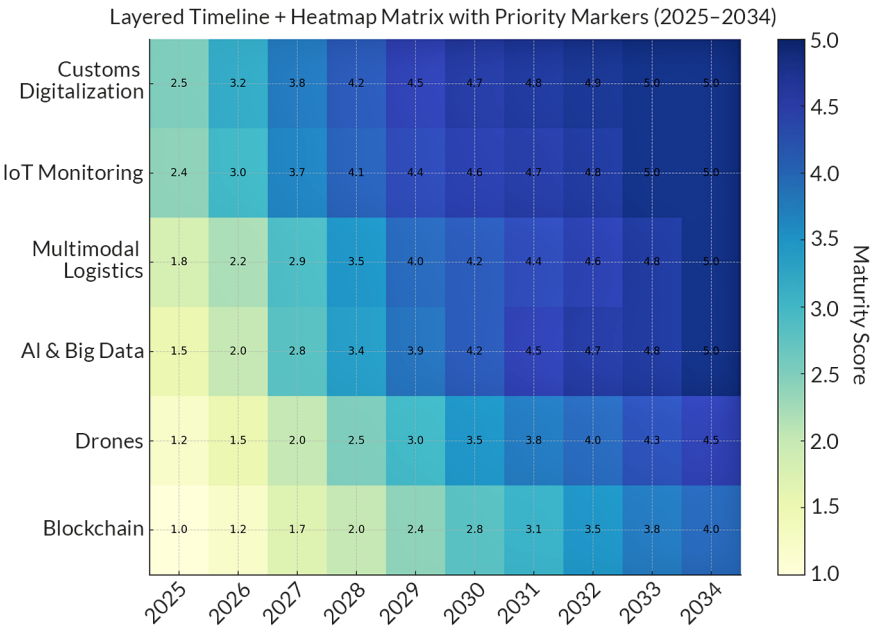


Fig. 5.8 "Roadmap" of the digitalization of Ukraine's TLS (2025–2034)

The above Layered Timeline + Heatmap Matrix diagram synthesizes the key results of the Diamond model, the digitalization priority matrix, the S-curve modelling, and the scenario forecast up to 2034.

The interpretation of the graph is as follows:

- the Y-axis represents the directions of TLS digitalization: from customs and IoT to drones and blockchain;
- the X-axis shows the years from 2025 to 2034;
- the color of the cells reflects the maturity level (from 1 to 5) for each direction in each year. The more saturated the color, the higher the maturity of digitalization in the respective direction.

At the conclusion of the study, special attention should be drawn to the practical significance of the visualized "Digitalization Roadmap" of Ukraine's TLS, which will undoubtedly influence managerial decisions, namely:

- the strategic drivers of digitalization – customs digitalization and IoT monitoring – reach the peak of maturity as early as 2027, and it is precisely with them that scaling should begin. These directions can ensure a quick return and compliance with EU requirements;
- multimodal logistics and AI demonstrate stable positive dynamics both in the near and long-term perspective. Their development and scaling require institutional coordination between sectors and support from the government;
- drones and blockchain demonstrate the slowest pace of implementation, which may be influenced by uncertainty in legal regulation and normative support (here the focus is primarily on their practical application in TLS), as well as certain integration barriers with international infrastructure and external funding. According to the authors of the monograph, they will require the creation of special pilot testing zones and digital "sandboxes" for trial implementation.

This visualization format has proven to be the most effective for assessing which directions require urgent governmental intervention and support, international technical assistance, as well as the application of a set of focused management measures.

5.6 Conclusion

Thus, it is possible to summarize that under conditions of severe resource constraints and extended investment horizons, traditional and linear approaches to restoring transport and logistics potential lose their effectiveness. They imply the recreation of the past, whereas the congruent model of digitalization is a movement forward, taking into account the experience gained as well as the transformation of internal and external environmental conditions. Within this model, the new domestic transport and logistics infrastructure will be designed from the outset as digitally integrated, automated, energy-efficient, and sustainable – which not only meets the

challenges of modernity but also positions Ukraine competitively within the future system of European logistics and smart routes.

The digitalization of Ukraine's transport and logistics system by 2030 and beyond is a complex, multi-stage process, dependent on a number of conditions. Analysis through the lens of Porter's model shows that the country possesses potential and drivers for success (strong factor conditions in IT, high demand for efficient logistics, partner support, and competition that stimulates innovation). The assessment of six priority areas of digitalization revealed that the greatest immediate impact will come from projects focused on digitalizing borders and multimodal logistics, as well as pervasive IoT monitoring. These areas form the foundation upon which more advanced technologies are deployed – Big Data analytics, artificial intelligence, drones, and blockchain.

The scenario forecast demonstrates a wide range of possible outcomes – from a breakthrough transformation of Ukraine into a digital logistics hub of Europe (under an optimistic set of circumstances) to slowed, partial progress (in the case of prolonged crises). The baseline scenario will most likely lead to gradual development and the achievement of key goals set for 2034 in the existing strategies. A crucial prerequisite for all scenarios remains the establishment of lasting peace and the attraction of investment for recovery. Nevertheless, even in the most favorable case, realizing the digital potential will require Ukraine to make consistent efforts: investing in education and human resources, strengthening cybersecurity, improving legislation and standards. It is necessary to ensure coordination between the state and business, project transparency, and a focus on the best global practices.

It is extremely important to shift from isolated IT initiatives to a comprehensive strategy covering the entire transport and logistics system. If all key elements come together, Ukraine will not only restore what was lost but also create a new, competitive, and resilient logistics infrastructure. As experts note, only such a comprehensive approach will allow for the formation of next-generation logistics, strategically oriented toward integration into the global economy. The digital transformation of transport will become one of the pillars of economic growth, increase investment attractiveness, and strengthen Ukraine's role as a transit bridge between Europe and Asia. Even today, despite all the difficulties, steps are being taken in this direction and the success of their implementation in the coming years will determine the country's logistics future by 2030 and beyond.

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CHAPTER 6

Digital transformation as a factor in the development of international business in the era of digital globalization

Robert Rogaczewski

Abstract

In the era of internationalization and digital globalization, digital transformation has become a key factor determining the nature of international business. Consequently, enterprises are now facing significant challenges. One of them is the need for comprehensive implementation of information and communication technologies, which undoubtedly impacts a company's success, especially on international markets. Digital transformation has ceased to be an exclusively technological trend and has become an indispensable strategy allowing enterprises to gain a competitive advantage. This is largely caused by the accessibility of tools such as artificial intelligence (AI), Big Data analysis, cloud technologies, blockchain and the Internet of Things (IoT).

The aim of this chapter is to highlight the importance of digital transformation and the role it plays as a driver of international business development. It attempts to analyze how digital transformation has become one of the key factors currently supporting the growth of international business in the context of digital globalization. The chapter also presents the level and scope of digital transformation in selected Central and Eastern European countries. Additionally, the author proposes an original index, which can be used to measure the level of digital transformation in the context of future international activities.

Keywords

Digital transformation, artificial intelligence, Big Data, blockchain, digital transformation indicator.

6.1 Introduction

In the face of increasing complexity and instability of the global economic environment reflected, for instance, in supply chains disruptions, geopolitical tensions

or growing expectations for sustainable development the importance of digital tools is clearly gaining ground. Today, digital technologies are becoming a crucial instrument that enables enterprises not only to survive but also to thrive under challenging market conditions. In the coming years, it will be the ability of organizations to effectively implement digital innovations and flexibly adapt to rapidly changing global conditions that will determine their competitive position on the international stage.

6.2 Digital transformation – theoretical and international perspectives

6.2.1 Digital transformation – a literature review

The advancement of transformational processes has driven the development of such technologies as artificial intelligence (AI), the Internet of Things (IoT), cloud computing, blockchain, and Big Data. Undoubtedly, these modern engines of economic growth contribute to the automation of production processes including the creation of Manufacturing Execution Systems (MES) and enable real-time behavioral analysis.

Digital innovations have significantly influenced consumer behavior and expectations, but above all, they have impacted business operations and their dynamic capabilities [1]. Digital transformation should be viewed as a multidimensional process that integrates digital technologies across all areas of an organization's activity [2]. It is not limited to the implementation of advanced technological solutions but encompasses changes in business models, organizational structures, management practices, and organizational culture [3]. The process of digitalization should be recognized as a future trend in the development of industry and logistics. It is based on information systems, which ensure increased functionality and networking [4]. The objective of digital transformation is therefore to increase operational efficiency, improve customer experience, and foster the development of innovative products and services [5].

It is also essential to refer to other definitions found in the academic literature. According to G. Vial, digital transformation is a process aimed at enhancing an entity by bringing about significant changes in its characteristics through a combination of information, computing, and communication technologies [6]. On the other hand, S. Kraus, S. Durst, J. J. Ferreira, P. Veiga, N. Kailer, A. Weinmann define digital transformation as the process of integrating digital technologies across all areas of an organization, leading to structural changes in how the organization operates

and delivers added value to its customers [7]. A. Hanelt, R. Bohnsack, D. Marz, C. Antunes Marante view digital transformation as an organizational change that is triggered and shaped by the widespread diffusion of digital technologies [8]. Thus, digital transformation should be understood as a transformation of the way digital technologies are utilized. These activities are intended to develop and implement a business model that supports the creation of added value and enhances its effective use by the organization.

It is also important to reference the flow model for digital transformation (**Fig. 6.1**).

Three types of external factors can be distinguished as key drivers of digital transformation. The first relates to digital technologies, which, over the years, have given rise to online payment systems, broadband Internet, and cloud computing. These elements now serve as a foundation for e-commerce sales. The COVID-19 pandemic also significantly accelerated the pace of digital transformation, highlighting the role of technologies such as artificial intelligence, blockchain, the Internet of Things (IoT), and robotics. The second factor – digital competition – has introduced profound changes in how enterprises compete. It is currently observed on a global scale and, through the growth of transnational corporations, relies on the exploitation of increasing volumes of data (Big Data) to achieve dominance in specific business sectors. The third factor involves changes in consumer behavior in response to the introduction of digital innovations. Consumer behavior has undergone substantial transformation due to, for example, the use of search engines and social media platforms. As a result, interdependencies in consumer behavior patterns have been intensified.

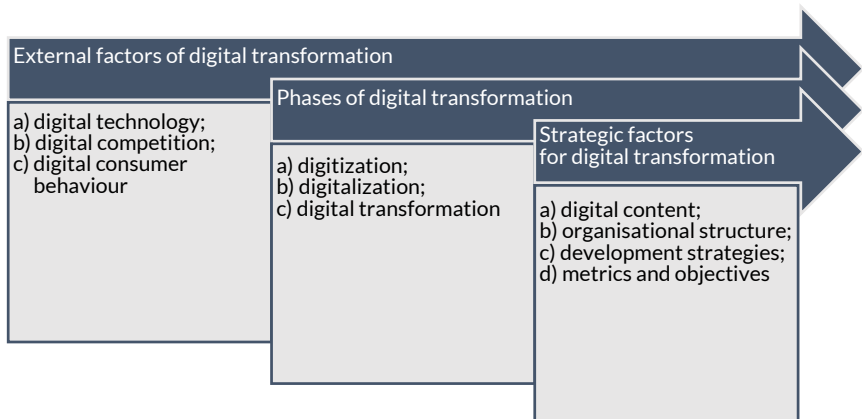


Fig. 6.1 Flow model for digital transformation
Source: compiled by the author based on [1]

An important component of digital transformation is its progression through distinct phases, i.e. digitization¹, digitalization² and digital transformation [9]. The first two phases are characterized by the gradual improvement of an enterprise's existing operations, while the final phase entails a more comprehensive digital transformation. To better illustrate the differences between these phases, the following comparative table provides a concise overview (**Table 6.1**).

Table 6.1 Characteristics of individual phases of digital transformation

Phase of digital transformation	Digital content	Organizational structure	Digital development strategies	Objective
Digitization	Digital assets	Regular hierarchical	Market penetration, product development and market development	Cost savings, more efficient allocation of resources across existing operations
Digitalization	Digital assets, digital agility, digital networking capability	Separate, agile units	Market penetration, product development, market development, platform-based market penetration, co-creation platform	Cost savings and increased revenues, more efficient production through business process reorganization, better customer experience
Digital Transformation	Digital assets, digital agility, digital networking capability, Big Data analytics capability	Separate units with flexible organizational structures, IT internalization and analytical functional areas	Market penetration, product development, market development, platform-based market penetration, co-creation platform, platform diversification	A new cost and revenue model, asset reconfiguration in the context of developing new business models

Source: [1]

Each of the aforementioned phases of digital transformation imposes specific demands on a company's digital resources, organizational structure, development strategies, and performance indicators. Enterprises, which primary objective is to pursue digital transformation must not only possess digital assets, but also acquire or develop capabilities related to digital agility, digital networking, and Big Data analytics.

¹ Digitization is the process of creating and developing documentation, which consists in transforming information in the analogue version into digital form. This makes it possible to process it using computers, as well as to store and transfer it

² Digitalization concerns the use of IT technology as a factor that will enable the use of new business opportunities based on the processes modified so far in the enterprise

6.2.2 Global technological trends affecting international business

Contemporary business is largely shaped by the dynamic development of digital technologies. Today, they constitute a key strategic pillar for business development in increasingly globalized economies. Globalization, driven by technological advancement, has enabled firms to expand more rapidly and efficiently into foreign markets. The emergence of global technological trends has been significantly influenced by the rise of technologies such as cloud computing, artificial intelligence (AI), the Internet of Things (IoT), 5G networks, and blockchain. These technologies are redefining the way business is conducted on international markets. The above-mentioned technological trends do not only support the optimization and automation of business processes but, more importantly, allow firms to tailor their offers to the specific needs and preferences of customers across different markets. On the other hand, analytic technologies, based on Big Data, empower organizations to make more accurate strategic decisions, thereby accelerating their global development. Global technological trends are thus reshaping international business by enabling enterprises to adapt to evolving market conditions and to compete more effectively abroad. It is therefore essential to examine these trends more closely.

The concept of *cloud computing*, as well as data processing in the cloud, was first introduced by S. Gillett and M. Kapor [10]. Cloud computing is based on or developed through solutions such as virtualization, network computing, utility of computer resources or autonomous computing. Selected definitions of cloud computing are presented in **Table 6.2**.

The analysis of the above definitions leads to the conclusion that cloud computing is a model of distribution of ICT solutions which, being accessible to users via a network (typically the Internet), are characterized by high availability, flexibility, and reliability, and are paid for based on actual resource usage (pay-as-you-go).

Whereas the process of internationalization itself previously involved physical activity and the transfer of a given company's capital to host markets, cloud computing has become the foundation for global business operations. Companies can now operate on a global scale without the need for physical presence in multiple markets and can scale their operations instantly [17]. Furthermore, several key benefits should be highlighted, particularly in the context of using cloud computing by companies operating internationally. These include, above all, global scalability (the ability to instantaneously launch services anywhere in the world), reduced market entry costs (no need to build physical IT infrastructure in each country), flexibility (easy adaptation of IT resources to the specifics and size of local markets), international collaboration (real-time access to data and systems from any location), and

compliance and security (cloud platforms provide the necessary solutions to meet local regulatory standards).

Table 6.2 Cloud computing – overview of definitions

Author(s)	Definition of cloud computing
E. Krok	Cloud computing can be defined as a remote, on-demand service that provides configurable hardware and software resources for storing and processing data
F. Etro	A new general purpose of Internet-based information technologies is to store data on external servers and deliver it as an on-demand service to clients
J. Staten	A form of computing in which massive, scalable, and accessible IT resources are provided as a service to external clients over the Internet
P. Mell and T. Grance	Cloud computing is a model that enables convenient and universal, on-demand network access to a shared pool of configurable computing resources (such as networks, servers, storage, applications, and services) that can be quickly provisioned and released with minimal management effort or interaction with the service provider
International Organization for Standardization (ISO)	Cloud computing is a paradigm that enables network access to a scalable and flexible pool of shared physical or virtual resources, with automated on-demand provisioning and management
M. Armbrust et al.	Cloud computing refers both to applications delivered as services over the Internet and to the hardware and system software in data centers that provide those services

Source: [11–16]

The Internet of Things (IoT) is a relatively new technology. It is a system of distributed, digitally interconnected identifiers, communicators, or sensors built into objects as well as carried or worn by people and animals, which can be identified and can transmit data over a telecommunications network without the need for human-to-human or human-to-computer interaction [18]. According to M. Porter and J. Heppelmann, the term "Internet of Things" was coined to reflect the growing number of smart, interconnected products and to emphasize the new opportunities they may bring [19]. Other authors claim that the Internet of Things refers to sensors and actuators embedded in machines and other physical objects, which purpose of application is to collect data, remotely monitor and make decisions and to conduct improvement processes in all areas of activity [20]. The Internet of Things could also be viewed as a global infrastructure that enables remote monitoring, control, and automation of physical objects over the Internet, using integrated sensor and network technologies [21].

Therefore, it should be emphasized that the Internet of Things is a system in which objects can communicate with each other with or without human intervention. According to M. Malucha, the construction of tools constituting the solutions for Internet of Things is based on [22]:

- objects equipped with sensors, detectors or transmitters that allow for communication, receiving commands, as well as collecting and transmitting information;
- IT systems and solutions that serve as recipients of the data collected and transferred by the objects, which are also responsible for processing the data and making decisions (e.g., laptops, tablets, smartphones, or home clouds);
- infrastructure enabling communication, i.e. transferring data between the objects.

To better illustrate the concept of the Internet of Things in business, it is necessary to identify the areas in which it supports the international operations of companies (Table 6.3).

Table 6.3 IoT in selected international companies

Name of company	Area of use	Example of use
Siemens	Industry 4.0/ Smart Manufacturing	IoT enables remote monitoring of machines, failure forecasting and automation of production processes in manufacturing facilities located in different countries. Siemens uses a platform called <i>MindSphere</i> to collect data from devices in its factories, thereby optimizing processes and minimizing downtime
Maersk	Smart Logistics	IoT enables real-time tracking of the location, temperature, humidity and condition of shipments, which is crucial for international transports. <i>Maersk</i> , the world's largest container shipping operator, uses IoT sensors to monitor transport conditions (e.g. in refrigerated containers), thus ensuring the safety of cargo and compliance with sanitary standards
Walmart	Retail	IoT enables the analysis of customer traffic, optimization of product placement, inventory management, and real-time offer personalization. Walmart uses IoT to manage refrigerator temperatures, track inventory, and automatically reorder goods
Tesla	Automotive & Mobility (Connected Vehicles)	IoT enables remote vehicle diagnostics, software updates, route optimization, and international fleet management. Tesla uses IoT to transmit data from its users' vehicles across various countries for diagnostic purposes, updates, and the development of autonomous driving
Hilton Hotels	Hotels & Tourism (Smart Hospitality)	IoT enables smart room management, guest experience personalization, and efficient energy use in globally operating hotels. <i>Hilton Hotels</i> has implemented IoT solutions that allow guests to control air conditioning, lighting, and entertainment through a mobile app across multiple countries

Source: compiled by the author

The concept called the Internet of Things is particularly important today. The Internet of Things, Services and Data, as it could be named, is becoming a crucial infrastructure that defines the next industrial revolution [4].

Another key component of modern technological trends is *blockchain*. This technology ensures secure and transparent transactions, which is of particular importance in international business. Blockchain is a distributed ledger technology used to structure, store, and transmit business information over the Internet. As its name suggests, blockchain is a decentralized data structure consisting of so-called blocks linked together in an unbreakable chain. These blocks store encrypted information [23].

In order to illustrate the areas in the company where blockchain technology is applied, it is worth examining the activities of selected international companies operating in this domain (Table 6.4).

Table 6.4 Use of blockchain technology in selected enterprises

Name of company	Scope of application	Example of use
IBM + Maersk (TradeLens), Carrefour, De Beers	Logistics & Supply Chain	Traceability and automatic recording of the flow of products
Ripple, JP Morgan (JPM Coin), Circle	Finance	Cross-border payments, smart contracts, asset tokenization
we.trade (blockchain platform of European banks)	International trade	Automation of commercial contracts with smart contracts
LVMH (Aura Blockchain), Prada, Cartier	Luxury & Fashion	Authentication of premium products (NFT, blockchain tags)
Walmart + IBM, Nestlé	Agriculture & Food	Logging the entire supply chain from farm to store
Sovrin Foundation, Microsoft ION	Personal Data Management	Decentralized digital identities (Self Sovereign Identity)

Source: compiled by the author

As evidenced above, the use of blockchain technology in various areas of international business operations may correlate with improved efficiency, reduced processing costs, enhanced transaction and product security, improved data quality, increased customer satisfaction and greater trust in the brand.

In the context of digital transformation and data management, Big Data and data analytics play a pivotal role. The term *Big Data* refers to data or sets of data that, due to their volume, cannot be processed using traditional applications. According

to A. Katal, M. Wazid, R. Goudar, Big Data involves such large volumes of data that it requires the implementation of new technologies and architectures in order to derive meaningful value from them [24]. Similarly, W. Fan and A. Bifet define the term as a dataset that cannot be managed by means of currently existing data mining methods or software tools due to its size and complexity [25].

Technology now has a tremendous impact on all spheres of the economy, business, and the state. Artificial intelligence, information and communication technologies, green technologies, biotechnology and blockchain confirm its leading role [26]. Global technological trends such as cloud computing, IoT, AI, 5G, blockchain, Big Data and sustainability significantly influence international business. Not only do they facilitate expansion into foreign markets but also transform how business is conducted, enhancing the efficiency, flexibility, and innovation of globally operating organizations. It is crucial to skillfully use these technologies to optimize processes, personalize the offer and introduce new business models.

Digital transformation is currently one of the key factors shaping how companies operate in international markets. In an environment of increasing competition, growing uncertainty and the need to ensure high operational efficiency, organizations are increasingly deciding to implement advanced technological solutions that enable process automation, data processing decentralization and dynamic management of global supply chains.

6.3 Digital globalization as a new environment for business development

6.3.1 The nature and importance of globalization in digital transformation

The spread of globalization, rising consumer demand, made-to-order production, lean management, shorter production cycles, and the rapid development of information technology are placing increasingly high demands on enterprises [27]. Globalization is perceived as a process encompassing all social spheres of a country and extending to international institutions, political and economic relations between countries, as well as changes in national economies and their domestic policies [28]. Today, it is defined as a process of growing economic interdependence driven by the rapid development of international trade and cultural exchange. The economic interpretation of globalization most often refers to business activities, economies, industry markets, enterprises, and the surrounding competition [29]. However, globalization is not just a concept used to analyze purely economic phenomena occurring in the modern global economy. It is often understood as a specific condition of

the world economy – namely, the liberalization of trade and capital flows, along with accelerating processes of integration and internationalization [30]. Globalization involves the intensification of capital, trade, service, and information flows on a global scale, leading to the merging of national economies and the formation of so-called transnational corporations [31]. These flows are initiated and stimulated by the most developed countries, but they do not occur without the participation of other market participants. In the context of globalization, those most likely to "survive" are the ones building transnational corporations [32]. An important aspect in the process of business globalization is the analysis of factors that have a direct impact on its development. The concept of globalization is usually examined from economic and political perspectives, which demonstrate both its positive and negative effects. In addition to its economic and political dimensions, globalization also includes technological, social, and cultural aspects.

Digital data has become especially important in today's world, serving as a critical resource in the global economy. Transnational corporations as well as small and medium-sized enterprises active in international markets use data to analyze and assess consumer behavior, manage global supply chains, optimize logistics processes, and tailor market entry strategies. Naturally, with the growth in the volume and value of data, the importance of digital platforms – such as Amazon, Google, and Facebook – has also increased. The emergence and development of digital platforms have rendered the notion of geographical borders rather secondary. Numerous businesses can now operate on foreign markets without the need for a physical presence in the host countries. Thus, establishing sales offices or subsidiaries is, in some cases, no longer justified.

Online platforms represent a specific type of business model that can take on various forms. M. Cusumano, A. Gawer, D. Yoffie distinguish three types of platforms: innovation platforms (which enable the development of new complementary products), transaction platforms (electronic marketplaces, which facilitate the exchange of goods, services, and information), and hybrid platforms (which combine the features of both previously mentioned types) [33]. In comparison, T. Doligalski identifies four types of platforms. He classifies the first two as community-based platforms, while the remaining two fall under the category of multilateral platforms [34].

Despite its many advantages, globalization driven by digital technologies faces numerous challenges. Among the most significant are the issues related to personal data protection, cybersecurity, the dominance of a few technological giants over global information flows, and limited access to digital infrastructure in certain parts of the world. These challenges are also faced by the world's largest online platforms, such as Netflix, which offers a wide range of content tailored to local markets and

Amazon, the largest online retailer, which enables cross-border sales and provides data storage services.

6.3.2 New forms of internationalization in the digital economy

Internationalization is the process of gradually involving a company in operations on foreign markets, based on growing experience with and knowledge of those markets [35]. It refers to the expansion beyond domestic markets with the aim of increasing sales, spreading risks, or gaining a competitive advantage [36]. Thus, internationalization involves extending economic activity beyond national borders. An important aspect of this process besides imports and exports is entering foreign markets. Internationalization, understood as the globalization of firms, markets, or institutions, is a dynamic process contributing to the globalization of the world economy. The dynamic conditions of globalization, combined with the nature of international business, make it possible to link macro- and microeconomic issues, especially in relation to multinational enterprises [29]. According to J. Rymarczyk, internationalization includes any form of business activity that a company undertakes abroad [37].

The definitions above emphasize that the internationalization of enterprises particularly in terms of active forms of foreign operations should traditionally involve the physical transfer of capital or know-how. However, modern digital technologies have fundamentally changed how companies approach international expansion. Instead of relying solely on a traditional physical presence in foreign markets, businesses increasingly adopt online-based solutions, ranging from online sales platforms and social media channels to cloud-based services. Classical models of internationalization typically requiring a company to establish a physical presence abroad are now being complemented by digital distribution channels and e-commerce platforms.

One of the key manifestations of change in modern international business is a phenomenon referred to as digital global expansion. That simply means conducting business in foreign markets with the help of information technologies [38]. In the context of economic globalization, increasing attention is being drawn to enterprises that are globally oriented since their establishment, commonly referred to in the literature as "born global". The main objective of these companies from the very beginning – is to enter foreign markets while leveraging digital solutions to scale and broaden their international reach [39]. Such companies are most often active in sectors like information technology, e-services, online education, or SaaS (Software as a Service) business models. Thanks to the digitalization of sales and customer service processes, the costs of entering foreign markets have been significantly reduced.

6.3.3 Internationalization of e-commerce

Digital transformation is a process in which organizations use digital technologies to change their business models, operational processes, and the way they deliver value to customers. In the international context, e-commerce is no longer viewed as merely a sales channel, but it has become a strategic tool of digital transformation, as it drives changes in business models, alters relationships with customers, and transforms the structure of competitiveness in the global market.

E-commerce (online trade) should be seen as the processes of buying and selling supported by electronic devices [40]. Hartman defines e-commerce as a specific type of e-business venture, centered around individual transactions using the Internet as the medium of exchange [41]. In general, e-commerce refers to a series of activities carried out to complete transactions through electronic means.

Three main forms of e-commerce can be distinguished:

- B2C (business to customer) – a business relationship between a company and an individual customer;

- B2B (business to business) – a relationship between two companies;

- C2C (customer to customer) – a type of transaction between private individuals.

E-commerce has become not only a new sales channel, but also a powerful tool for transforming business models and internationalizing enterprises.

The ongoing digitalization of commerce has led to the emergence of various types of sales platforms, which enable businesses to operate effectively in the online environment. Depending on how they function and the degree of control over sales processes, three main types of e-commerce platforms can be distinguished:

- open-source – software that can be freely modified or extended with custom plugins;

- SaaS (Software as a Service) – cloud-based software services providing infrastructure and servers for running an online store;

- dedicated platforms – custom-built e-commerce solutions created from scratch, often tailored to specific business needs [42].

According to H. Brdulak, the share of e-commerce in retail sales varies. It depends on the level of digitalization in a given country and consumer habits, ranging from a few to several percent. A steady increase in the share of e-commerce in total retail sales is therefore evident [43].

Thus, it is worth analyzing the development of e-commerce within the European Union. From a statistical standpoint, in 2023, 17.7% of businesses in the EU conducted e-sales exclusively via websites or apps, 3.1% used only Electronic Data Interchange (EDI), and another 3.1% applied both methods. Among EU enterprises,

turnover from e-commerce via own websites or apps in 2023 was nearly six times higher than via marketplaces. In the accommodation sector, 99.6% of EU businesses engaged in e-sales in 2023 received orders through websites or applications.

Notably, between 2013 and 2023, the share of companies in the EU conducting online sales increased from 17.21% to 23.83%. Meanwhile, their turnover from e-commerce rose by 5.31 percentage points – from 13.81% to 19.12% – although the 2023 turnover was 0.71 percentage points lower compared to the peak level recorded in 2019 (**Fig. 6.2**) [44].

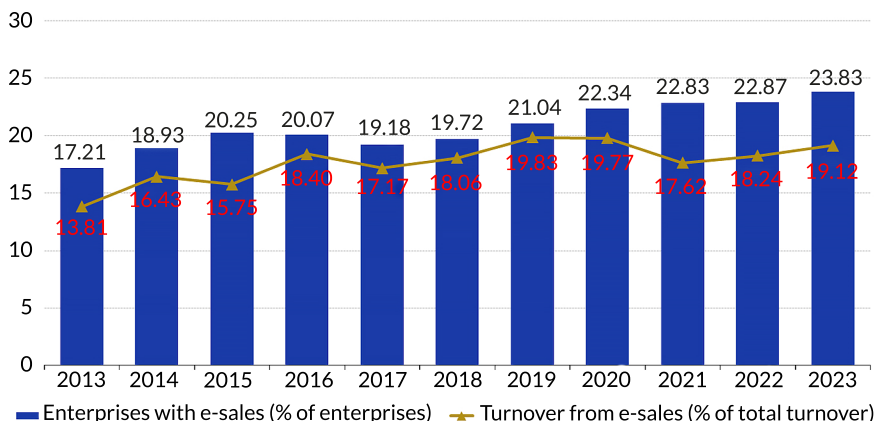


Fig. 6.2 E-sales and turnover from e-sales, EU, 2013 to 2023

Source: [44]

The level of engagement in e-commerce and the share of e-sales in total enterprise turnover in 2023 varied significantly depending on company size. Among large enterprises, 46.45% engaged in electronic sales, with revenues from this channel accounting for 24.44% of their total turnover. For medium-sized companies, 30.51% conducted e-sales, which constituted 14.99% of their total revenue. In contrast, the lowest level of engagement was recorded among small enterprises, with only 21.88% of them selling online and generating 9.49% of their total turnover that way (**Fig. 6.3**).

E-sales can be conducted through websites or mobile applications (internet sales), or carried out automatically via Electronic Data Interchange systems. Companies may offer one or both of these options to their customers. In 2023, among EU countries, the proportion of companies engaged in e-sales ranged from 12.20% in Luxembourg and 14.74% in Romania to 42.07% in Lithuania, followed by Ireland (39.57%), Denmark (38.76%), and Sweden (36.50%) (**Fig. 6.4**).

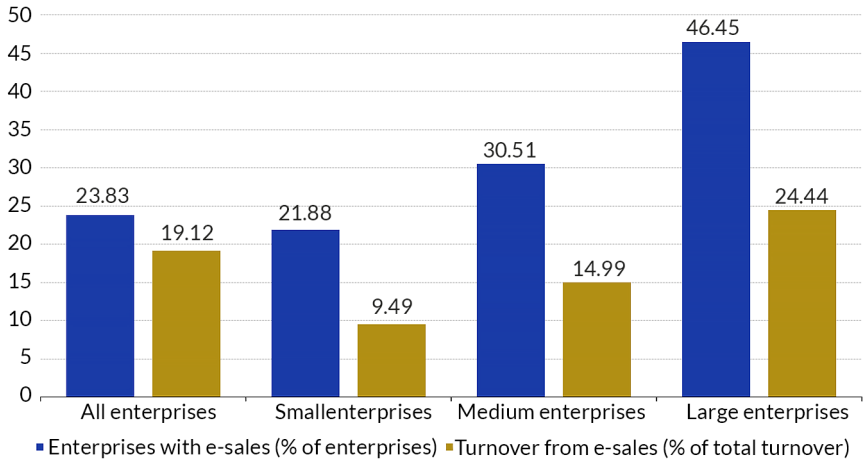


Fig. 6.3 E-sales and turnover from e-sales, by size class, EU, 2023

Source: [44]

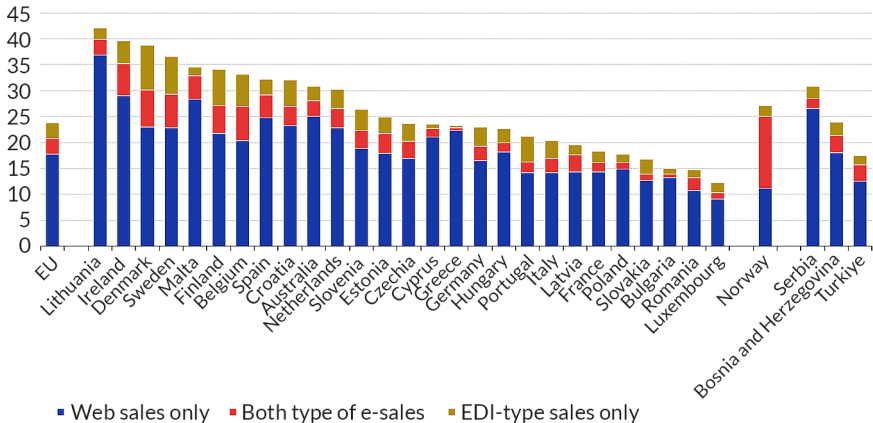


Fig. 6.4 E-sales broken down by web sales and EDI-type sales, 2023 (% of enterprises)

Source: [44]

In 2023, 17.69% of companies in the EU conducted e-sales exclusively via websites or apps, 3.08% used only EDI, and 3.06% employed both channels. Internet sales remained the dominant form of e-commerce across all EU member states. The share of businesses receiving orders solely through websites or mobile apps ranged from 36.89% in Lithuania to 9.09% in Luxembourg. As companies increasingly

recognize the importance of online presence, websites and mobile apps have become popular sales tools, enabling customers to place orders conveniently online. On the other hand, the proportion of firms relying solely on EDI for e-sales varied from 8.72% in Denmark and 7.23% in Sweden to under 1% in Greece (0.44%) and Cyprus (0.87%). The highest percentage of enterprises using both internet sales and EDI was observed in Denmark (7.06%) and Belgium (6.55%), while the lowest was in Greece (0.47%) and Bulgaria (0.74%).

According to the data presented in **Fig. 6.5**, in 2023 nearly all businesses operating in the "Accommodation" sector and conducting e-sales (99.55%) received orders via websites or mobile applications. In contrast, 8.36% of these businesses used EDI system to carry out sales.

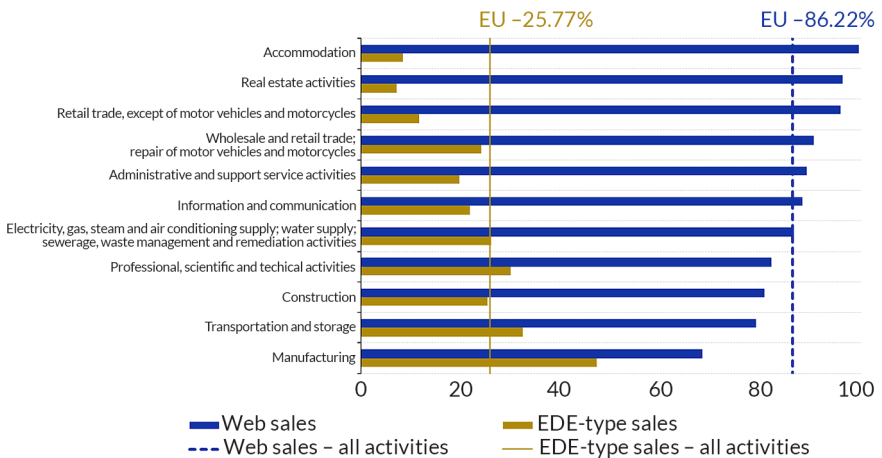


Fig. 6.5 E-sales broken down by web sales and EDI-type sales, by economic activity, EU, 2023 (% of enterprises with e-sales)
 Source: [44]

Nearly half of the enterprises in the "Manufacturing" sector engaged in e-sales reported receiving orders via EDI (47.10%). Other sectors with a high percentage of companies using EDI included "Transportation and storage" (32.34%) and "Professional, scientific and technical activities" (29.96%). Among manufacturing companies, the share of firms using websites or applications for e-sales and those using EDI was relatively close – 68.26% and 47.10%, respectively. In other sectors of the economy, sales were primarily conducted through websites or mobile applications (**Fig. 6.5**).

Among small e-commerce enterprises, 89.40% conducted sales via websites, while 20.22% used EDI. In the case of medium-sized enterprises, the difference between the shares of sales made through these two channels was smaller, with 78.12% of companies selling online and 39.15% using EDI. The smallest difference between these two types of sales occurred among large enterprises (Fig. 6.6).

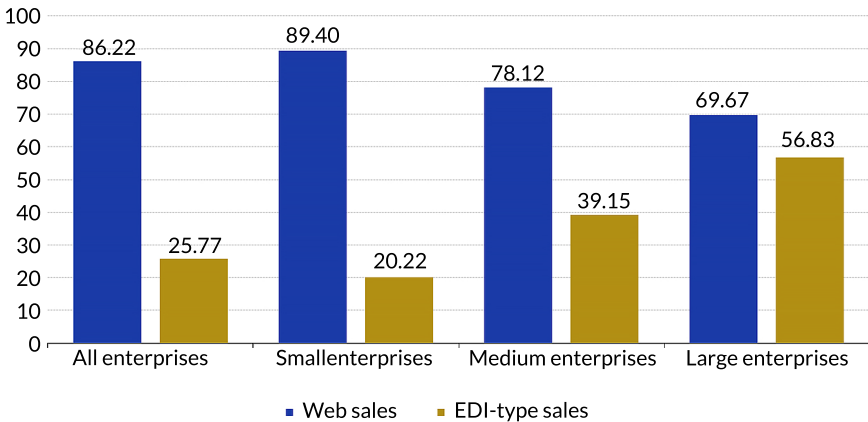


Fig. 6.6 E-sales broken down by web sales and EDI-type sales, by size class, EU, 2023 (% of enterprises with e-sales)
Source: [44]

The results of the e-sales analysis across various industries and companies of different sizes reveal significant differences in preferred online sales channels. In 2023, sales through websites and mobile applications were the most commonly used form of e-commerce, especially in the Accommodation sector, where almost all companies relied on this channel. In contrast, the use of EDI was more prevalent in the Manufacturing, Transportation and storage, and Professional, scientific and technical activities sectors. Small enterprises predominantly opted for internet-based sales, while medium and large companies were more likely to combine both channels, demonstrating a more balanced approach.

In the context of internationalization, digitalization acts as a key catalyst, removing traditional barriers associated with entering foreign markets, such as high logistics costs, the need for physical presence, or the development of extensive distribution networks. The use of digital tools enables companies to achieve international reach while also facilitating real-time data collection and analysis, allowing them to tailor their offers precisely to local needs and expectations. As a result, digital

transformation not only supports the internationalization process but increasingly becomes a prerequisite for companies seeking to operate internationally.

When analyzing digital transformation, it is important to consider the Digital Economy and Society Index (DESI) of selected EU countries. This tool, developed by the European Commission, allows for tracking the progress of digital development within EU member states. It enables the evaluation and comparison of the level of digitalization across countries and highlights the areas requiring further action or support [45]. DESI is based on four main pillars:

- human capital – assessing citizens' digital skills, both basic and advanced (e.g., in ICT);
- connectivity – analyzing digital infrastructure, including the availability of high-speed internet, 5G network development, and quality of online services;
- implementation of digital technologies by companies – measuring the adoption of modern technological solutions by companies, such as cloud computing, data analytics, or online sales;
- digital public services – evaluating the digitalization level of public administration, access to e-health services, and the use of open data.

The DESI index also plays an important role from the perspective of company internationalization, as a country's high level of digitalization creates favorable conditions for conducting business on international markets. Countries that score high on the DESI ranking provide companies with:

- a developed and stable technological infrastructure;
- access to qualified ICT professionals;
- favorable conditions for the development of e-commerce and digital services;
- a modern, efficient public administration available online.

To illustrate the DESI index level in selected Central and Eastern European (CEE) countries, it is worth analyzing it across several dimensions.

The first indicator showing the level of DESI is online sales by SMEs (**Fig. 6.7**).

Between 2021 and 2023, the highest share of enterprises engaging in online sales (30% of all enterprises) was recorded in Lithuania, while the lowest was observed in Romania and Bulgaria. In the case of Bulgaria, a moderate annual growth rate in the share of enterprises selling online is noticeable.

Among the countries of Central and Eastern Europe and Germany, the highest percentage share of enterprises, relative to all enterprises using big data, was observed in Germany. Since 2019, a steady, moderate annual growth rate has been visible. All EU countries have also shown a moderate annual growth rate. However, for some countries, 2019 marked the beginning of significant declines in the share of enterprises using Big Data. These countries include, most notably, Lithuania, Romania, and Slovakia (**Fig. 6.8**).

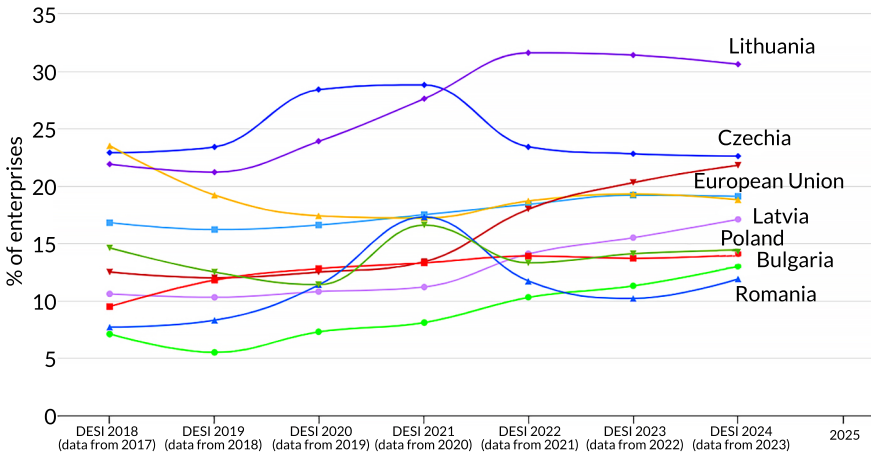


Fig. 6.7 SMEs selling online, Small and medium-sized enterprises

Source: based on [46]

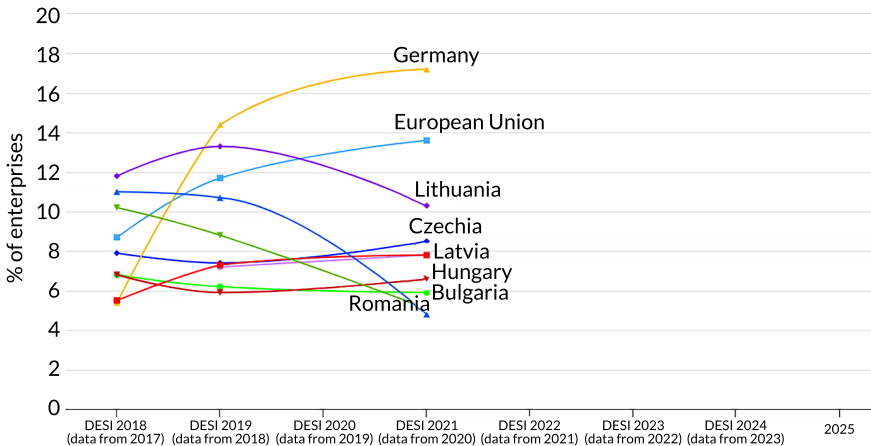


Fig. 6.8 Big Data, small and medium enterprises

Source: based on [46]

Therefore, it is worth mentioning the Digital Intensity Index (DII) in selected countries of Central and Eastern Europe (**Fig. 6.9**).

The share of enterprises with a high or very high Digital Intensity Index in EU countries stood at 34.3%. In Poland, this figure reached 33.2% in 2024, ranking

17th among all EU member states. The lowest shares of enterprises with a high or very high DII were recorded in Bulgaria and Romania, at 17.6% and 23.0%, respectively.

The use of artificial intelligence by enterprises in selected European countries should also be analyzed (Fig. 6.10).

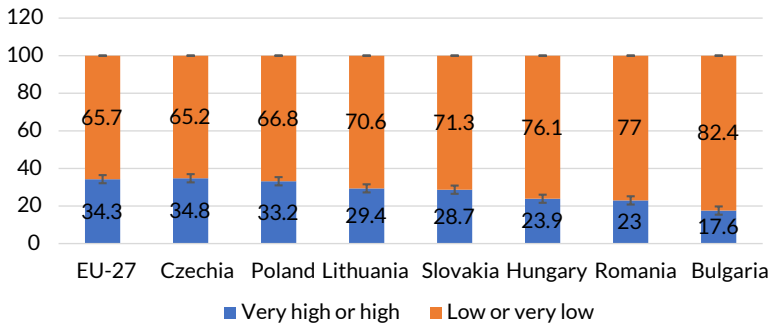


Fig. 6.9 Enterprises by level of DII in selected CEE countries in 2024 in % of enterprises
Source: compiled by the author based on [47]

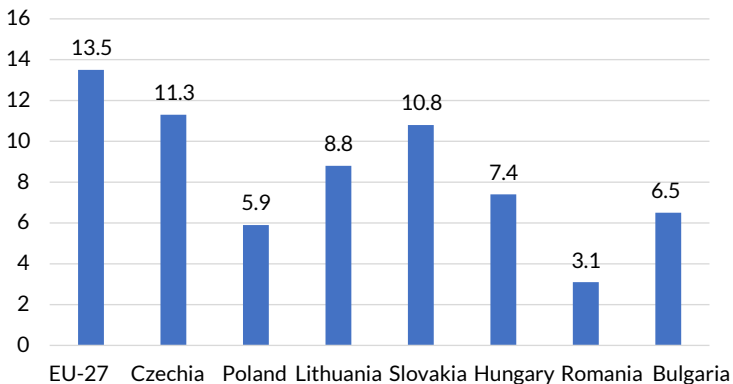


Fig. 6.10 Use of artificial intelligence in countries (2024, % of enterprises)
Source: compiled by the author based on [47]

The lowest share of enterprises using artificial intelligence was observed among Polish and Romanian companies, with only 5.9% and 3.1% of enterprises, respectively, making use of AI.

Digital innovations have a significant impact on consumer behavior and expectations, but, most importantly, they shape intelligent logistics and transportation

systems [48]. An increase in a country's DESI score contributes to enhancing its economic competitiveness and the quality of life of its society. As a result, foreign investments are intensified, highly qualified professionals are attracted, and the citizens can access advanced digital and infrastructural services more easily.

6.4 Digital transformation index in an international context

To determine the impact of digital transformation on a company's capacity for international expansion, it is proposed to develop an Enterprise Digital Transformation Index (EDTI). For the construction of this instrument, the following variables need to be considered:

1) country digitalization – the level of digital development in the country where the enterprise operates should be determined using available statistical data, such as the DESI index or other country digitalization indexes;

2) company digitalization – the level of a company's digital maturity should be assessed, for example, using a four-point scale:

- lack of a digital strategy in the enterprise (1 point);
- implemented ERP/CRM systems, digitalized processes (2 points);
- implemented ERP/CRM systems, digitalized process, integrated tools, automation, e-commerce (3 points);
- implemented ERP/CRM systems, digitalized process, integrated tools, automation, e-commerce and at least digital strategy, Big Data and AI (4 points).

The formula will therefore be as follows

$$EDTI = \frac{HCD + ED}{2},$$

where *EDTI* – Enterprise Digital Transformation Index; *HCD* – Host Country Digitalization Level; *ED* – Enterprise Digitalization Level.

It should be assumed that as the level of an enterprise's digital transformation increases, so does its readiness to engage in internationalization activities.

6.5 Conclusion

Digital transformation is a long-term and costly process of implementing digital technologies into a company's operations. Its primary goal is to increase efficiency, foster innovation, and improve the quality of services provided. In the global

context, digital transformation plays a crucial role in building competitive advantage. Enterprises with a higher level of digitalization are better equipped for international operations. Digital transformation has a significant impact on economic development, innovation, and integration with global markets, and today constitutes an important element of development strategies – both at the national and international levels.

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CHAPTER 7

Smart economy in the conditions of post-war recovery of Ukraine: digital tools of remediation and their impact on regional development

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Viktor Nadtochii
Anatolii Nadtochy

Abstract

This study is devoted to an in-depth exploration of the concept of "smart economy" in the context of post-war remediation and revitalization of Ukraine, with a focus on the application of digital tools in these processes through the lens of regional development. The relevance and significance of digital transformation for the prompt and effective recovery of the country after the military aggression are indisputable, as the future format of a revived Ukraine directly depends on it. The authors have developed and proposed a theoretical and methodological justification as well as empirical testing of an architecturally hybrid and context-sensitive model of smart economy for digital recovery, based on the integration of digital solutions with regional conditions, behavioral perception of the population, and institutional support. The methodology of the research is based on an interdisciplinary synthesis of systemic, adaptive, behavioral, and bio-inspired approaches. In the framework of the simulation, modern tools were used (Python, Jupyter Notebook, QGIS, SPSS), along with real data on internet coverage, usage of the Diia and eRecovery platforms, as well as indicators of recovery (RI) and population engagement. The proposed model allows not only to diagnose the current level of digital receptiveness of a region, but also to forecast the "activation point" of digital growth, identifying priorities for digital remediation and reconstruction. The practical significance of the work lies in its applicability for the development of regional digitalization strategies in the context of post-war recovery, as well as an analytical tool for public authorities and international partners.

Keywords

Post-war recovery, remediation, smart economy, regional development, phenotypic adaptation, inclusivity of digitalization, regional stratification.

7.1 Introduction

As a result of the full-scale military aggression that began in February 2022, Ukraine has suffered colossal destruction of infrastructure, industry, and housing. According to estimates by the World Bank and the government, the direct damage to infrastructure amounts to tens of billions of dollars, while full economic recovery will require hundreds of billions. However, the post-war reconstruction presents a unique opportunity not merely to restore what was lost, but to "reboot" the economy based on new principles. President Volodymyr Zelenskyi, even before the war, declared a course toward digitalization, aiming to build a "state in a smartphone", and by the beginning of 2022 Ukraine had achieved substantial progress: more than 10 million citizens (approximately one-third of the adult population) had installed the Diia application for access to electronic public services [1]. It can be confidently stated that this project laid the foundation for the future development of the smart economy. Paradoxically, the full-scale war further stimulated the accelerated scaling of digital transformation. The necessity for the state and businesses to function under conditions of hostilities and mass population displacement served as an impetus for the accelerated implementation of digital solutions. Mass use of electronic documents and services during the war became routine: Ukrainians increasingly use digital passports when necessary, receive payments and humanitarian aid via online platforms, etc. [2]. According to studies, over the years of the war, the level of Internet penetration increased from 62% in 2019 to 78% in 2023, and the number of users of online government services reached record values [3]. All the facts listed above indicate that digitalization has become an integral part of the state's resilience and adaptation in emergency conditions such as war.

It is logical that, after the cessation of hostilities, Ukraine will face a simultaneous triple task, namely: restoring the destroyed potential by eliminating the consequences of military activities (through a set of remediation measures), ensuring rapid recovery of the socio-economic system, and conducting informational and technological modernization according to the best global standards [4].

Ukraine's post-war recovery requires a transition from traditional centralized management to a smart, flexible, and inclusive model of regional development, in which digitalization plays not an auxiliary but a system-forming role. Under conditions of destroyed infrastructure, demographic instability, institutional failures, and

limited access to basic services, the key issue becomes not merely the availability of digital solutions, but their real acceptance and ability to become a platform for inclusive growth [5]. Modern research shows that successful digital transformation is impossible without digital convergence – that is, without integrating digital platforms, data, and solutions at all levels: from local united territorial communities (UTCs) to a unified territorial system. Only such integration will allow the formation of a unified digital space capable of serving as a catalyst for the smart economy and reducing territorial and social gaps [6].

However, according to the authors' vision, digital convergence is not only an infrastructure issue. Socio-psychological aspects and the behavioral readiness of the population to accept digital solutions become key barriers or, conversely, conditions for success. Precisely the aspects mentioned above determine the necessity of conducting empirical analysis.

Thus, the focus of this research is an inclusive smart economy, in which digitalization is considered not as an end in itself, but as a mechanism for sustainable, equitable, and adaptive post-war recovery of regional growth [6]. Within the framework of digital remediation, the authors of the monograph will deeply study the integration of digital convergence, behavioral receptivity, and territorial adaptation, which can become a strategic key to solving the complex of problems related to Ukraine's post-war revival.

The aim of the study is the theoretical substantiation, development, and empirical testing of an architecturally hybrid and context-sensitive model of Ukraine's digital recovery based on the principles of the smart economy, taking into account regional characteristics and differences in digital perception, institutional activity, and the degree of destruction. In accordance with this aim, the following objectives were identified: to systematize scientific approaches to understanding the smart economy in the context of crisis and post-crisis recovery; to develop the causal architecture of the digital recovery model; to conduct regional stratification of the territories of Ukraine based on simulation analysis and to justify strategic scenarios of digital intervention; to test the model using the example of three regions (Kherson, Chernihiv, and Ternopil area's), differing in the level of destruction, digital involvement, and institutional activity; to validate the model and formulate conclusions on its applicability for the development of strategies for regional recovery and digital transformation.

7.2 Theoretical and methodological basis of the research

Digital remediation in the context of regional development means the integration of digital technologies and intelligent solutions into remediation processes and

the subsequent socio-economic recovery of territories affected by military operations, emergencies, or technological accidents. In this aspect, digitalization acts as a catalyst for remediation, significantly increasing the efficiency of damage assessment, planning of restoration works, as well as forecasting possible risks and subsequent adaptive management. Geographic Information Systems (GIS), unmanned aerial vehicles (drones), Internet of Things (IoT), Digital Twins (DT) and Artificial Intelligence (AI) technologies become key instruments of digital remediation, allowing rapid and accurate inventory of damage, identification of the most vulnerable territories, and prioritization of restoration activities [7, 8]. According to the authors' conviction, digitalization of remediation serves not merely as a mechanism for eliminating consequences, but rather as a strategic driver of a new quality of regional development based on data, intelligent platforms, and active citizen participation. The close correlation between the digitalization of remediation and the socio-economic recovery of regions is due to the fact that smart digital management of remediation can serve as a systemic mechanism for the revitalization of affected territories, ensuring sustainable growth based on the principles of adaptive management, digital inclusion, and civic participation.

To comprehensively study the above-defined problem area, the authors employed a synthesis of interdisciplinary approaches, modern scientific concepts, and original methodological solutions, including phenotypic adaptation, emergent strategy, a behavioral approach to remediation perception, and principles of inclusive digitalization [9].

Digital convergence as a connecting factor between elements of the model. It is proposed to begin the decomposition of the theoretical and methodological foundation with digital convergence. It is convinced that it is located at the core of the architecture of the smart economy and the effective remediation of war-affected territories in Ukraine. It is precisely digital convergence that ensures the coherence, compatibility, and scalability of digital solutions implemented in regions with varying degrees of destruction, recovery, and social receptiveness.

Digital convergence refers to the interpenetration and merging of various technologies, platforms, and industries in the digital age. It combines diverse digital technologies, such as GIS, artificial intelligence, and smart devices, with business models and processes to stimulate innovation as well as digital transformation. In the present study, digital convergence is understood as the process of technological, organizational, and institutional integration of digital platforms, data, services, and standards between:

- different levels of the structural hierarchical territorial system;
- sectors of the economy (industrial sector, transport and logistics, housing and communal services, healthcare, agriculture);

- elements of digital infrastructure (GIS, AI platforms, ML, blockchain, IoT, etc.);
- national digital initiatives (including such as Diia, Prozorro, DREAM, EcoCity, etc.) (Fig. 7.1) [10].

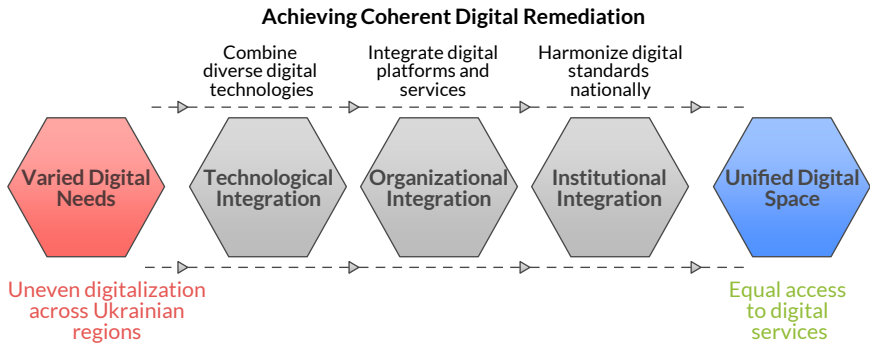


Fig. 7.1 Key results of coherent digital remediation

Digital convergence is based on the approaches of digital cohesion (EU), the concept of "smart connectivity" as well as the logic of constructing architecturally resilient digital systems, where modular components interact through standardized interfaces and form a unified digital space of remediation.

According to the authors, it is digital convergence that serves as the unifying layer that will ultimately enable:

- the scaling of successful digital practices from isolated pilot projects to the national level;
- the synchronization of remediation, reconstruction, and recovery processes between individual territorial units and regional centers;
- the provision of equal access to digital services, regardless of geographical location and the level of destruction of territories affected by military actions.

This is especially relevant for Ukraine, where the disparity between the level of digitalization and institutional capacity, the extent of destruction in regions as a result of military actions, and the digital need of territories is significantly varied.

The author's interpretation of the concept of "digital convergence" is that it is a multi-component and multi-level process of systemic and purposeful integration of digital technologies, platforms, data, standards, and services into a unified, architecturally sustainable digital ecosystem that ensures compatibility, interconnection, and scalability of digital solutions at all levels of governance and in all sectors of the economy. This reflects not only technological compatibility, but also methodological,

institutional, and territorial coherence, without which sustainable and inclusive digital recovery of Ukraine is impossible. This element performs an architectural linking function, ensuring the coherence and compatibility of digital solutions. Digital convergence serves as the infrastructural framework for the entire methodological model.

Digitalization as an inclusive mechanism of remediation and recovery of Ukraine's territory. This mechanism serves as the goal-forming foundation of the entire model. It defines the normative framework: the use of specific digital technologies for the purpose of post-war recovery of the country should not merely be applied as technical solutions, but should function as a tool of spatial and social justice, allowing equal opportunities for their use in all regions, regardless of the degree of destruction and institutional capacity.

This is especially important in the context of imbalance between severely affected territories and relatively preserved ones.

According to the authors, it is precisely this element of the methodological model that is capable of ensuring equal access to the opportunities of digitalization, their transparency, and scalability.

Thus, digitalization plays the role of an inclusive, and therefore fair, mechanism for engaging the population and municipal authorities first in the processes of remediation, and then in the revitalization of war-affected territories (Fig. 7.2).

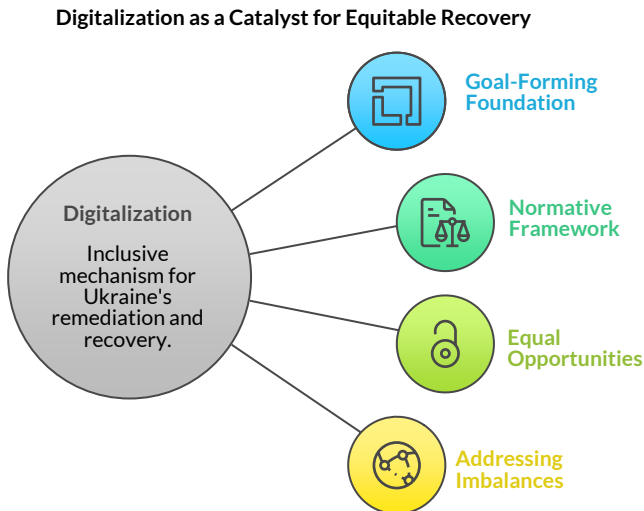


Fig. 7.2 Essence of the inclusive approach for the purposes of digital regional development

Behavioral perception of digitalization as a behavioral modifier of effectiveness. The authors of the monograph, in the course of an in-depth study of the issues of successful digitalization, came to the conclusion that the population must be ready to perceive digital tools – otherwise, they simply will not work. It was established that in the context of instability caused by varying degrees of destruction, digital initiatives are perceived by the population ambiguously and depend primarily on the satisfaction of basic needs and public trust.

Ignoring behavioral aspects can lead to an overestimation of the expected effects of digital initiatives, without taking into account that the population of regions with a high degree of destruction and a low level of recovery may not perceive digital technologies as a priority or important. Behavioral perception of digitalization in the methodological model plays the role of a behavioral filter. Without taking this approach into account, digitalization will be ineffective even in the presence of infrastructure; it allows formalizing the differences between regions with the same level of digital saturation but with different effectiveness.

Thus, digital transformation of regions in post-war Ukraine cannot be implemented without integrating the behavioral aspect of the population's perception of digital technologies. It is precisely the use of this approach that can ensure the sustainability and adaptability of digital strategies for regional development under conditions of uncertainty, as well as form the basis for further practical recommendations on the implementation of regional digital transformation in Ukraine (Fig. 7.3).

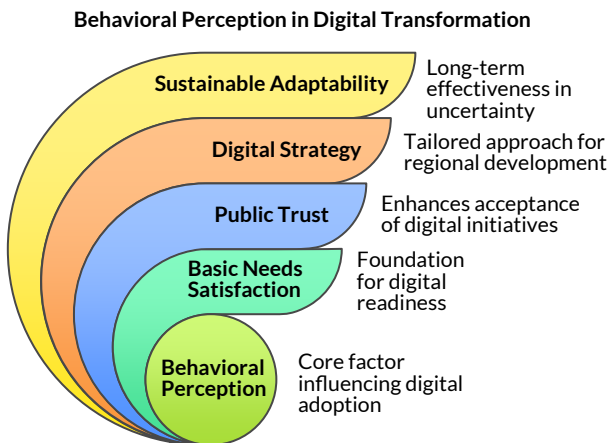


Fig. 7.3 Characteristic of behavioral perception of digital transformation of regional development

Phenotypic adaptation as a flexible adaptive architecture of regional development. This is a methodological principle borrowed from biology, in which digital solutions are not defined centrally, but evolve and adapt to the conditions of a specific region: destruction, resources, perception, infrastructure. In the commonly accepted sense, phenotypic adaptation represents the ability of an organism to change its phenotype (referring to external characteristics and behavior) in response to environmental changes, despite having the same genotype. The expediency of borrowing bio-inspired approaches has already been deeply studied, including in the scientific works of the authors of this monograph [7, 11, 12].

Further developing this scientific approach, the authors of the monograph concluded that under post-war remediation and recovery conditions, it is necessary to differentiate regions, since they have different levels of destruction, resource potential, digital maturity, and social capital.

In this regard, the strategy of identical digital solutions for all regions will not work.

Why not a centralized Smart Nation, but rather a dispersed Smart Regions strategy should be prioritized?

Phenotypic adaptation (PA) will allow to:

- ensure institutional and behavioral flexibility of digitalization;
- dynamically adapt services, architecture, and digital development strategies to local conditions;
- minimize the risk of digital rejection and inefficiency, especially in zones of destruction and social instability;
- create a foundation for building digital development trajectories oriented toward the real level of regional recovery after a complex of remediation measures.

Thus, in the authors' view, PA is capable of optimizing the implementation strategy of Smart Regions to the maximum extent possible, because it allows for the formation of localized phenotypes of digital solutions based on the contextual criteria of each region. Instead of a "one-size-fits-all" Smart Nation strategy template, it will be much more effective to implement a network of regional digital ecosystems capable of maximum adaptation, but not unification (**Fig. 7.4**).

Digitalization as a factor of sustainable regional development. In this study, the authors consider digital transformation as a long-term driver of socio-economic and spatial development at the level of territorial communities and within the regions of the country as a whole. It refers primarily to the idea that digitalization is not only and not so much a key factor in effective remediation and post-war recovery, but also a strategic driver of a new quality of regional development, based on the principles of sustainable development and environmental safety [13].

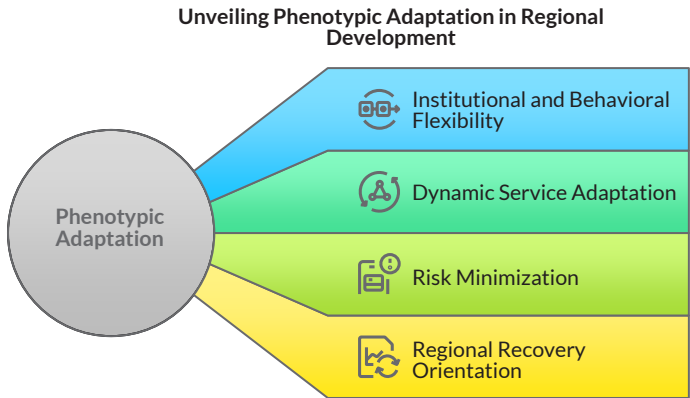


Fig. 7.4 Essence of phenotypic adaptation in the context of digital regional development

Digitalization is capable of integrating actual and potential resources into economic, social, and spatial development strategies, transforming the step-by-step post-war recovery into sustainable growth. This structural element of the methodological model reflects the success of digital transformation not in isolation, but as a result of a complex influence – the level of digital need, the quality of technological integration, and the population's readiness for progressive digital practices. Thus, digitalization is considered not as a goal, but as a tool of regional development, productivity enhancement, and institutional resilience of regions (**Fig. 7.5**).

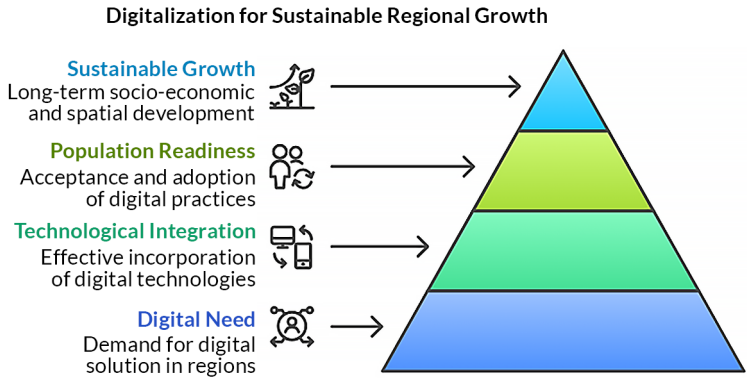


Fig. 7.5 Essence of digitalization for the purposes of sustainable regional development

All the above-mentioned structural components are interdependent and methodologically complementary, and therefore must be fully included in the theoretical and methodological model. They ensure the architectural, behavioral, institutional, and regional integrity of the smart economy model in the context of Ukraine's post-war recovery.

The research is based on the following scientific concepts (**Table 7.1**).

For building the model, a synthesis of classical and modern scientific approaches was used (**Table 7.2**).

Table 7.1 Theoretical foundations of the study

Theoretical basis	Significance for the study
Smart Economy Concept	Foundation of digital transformation based on data, innovation, GIS, AI, IoT, ML, and platform solutions
Theory of Sustainable Regional Development	Justification of the need for balanced development of all territories
Theory of Digital Inclusion	Guarantee of equal participation of all regions and social groups in digital platforms and services
Concept of Phenotypic Adaptation	A digitalization model that adapts to local conditions: destruction, resources, level of trust
Emergent Strategy (Mintzberg)	Strategies and digital solutions are formed from local practices, not imposed top-down [14]
Smart Connectivity	Ensures structural connectivity of regions, services, and solutions
Unified Digital Space	Operationalization of digital convergence in the architecture of the remediation model

Table 7.2 Methodological approaches used in the study

Methodological approach	Function
System Approach	Study of digitalization as a system of interacting elements: subsystems, technologies, people, processes
Comprehensive Approach	Consideration of multifactoriality: social, infrastructural, behavioral, and digital factors
Cybernetic Approach	Ensuring feedback, self-regulation, and controllability of the digital remediation system in a dynamically changing environment
Regional Governance Approach	Adaptation of digital strategies to regional specificities, coordination of actors, and decentralization of decision-making
Adaptive Approach	The model's ability to adapt to changing conditions of remediation and post-war recovery
Situational Approach	Decision-making based on the specific conditions of a region
Synergetic Approach	Mutual reinforcement of digital and institutional mechanisms in remediation
Bio-Inspired Approach	Phenotypic adaptation and emergence as a catalyst for digital regional development

The developed and presented theoretical and methodological foundation of the research integrates systemic, behavioral, technological, and institutional aspects of Ukraine's recovery. Digital remediation is considered as a tool not only for development but also for inclusion, resilience, and social justice. According to the authors of the monograph, it is precisely this approach that contributes to the formation of the basis for a smart, sensitive, and differentiated strategy of remediation and post-war recovery of Ukraine, which is necessary for long-term success.

7.3 Architecture of the methodological framework and the smart economy model of Ukraine's digital recovery

It is possible to assess how digital technologies actually influence remediation and subsequently the further development of Ukraine's regions, depending on the behavioral perception of the population, the adaptiveness of solutions, digital connectivity, and institutional support, through an architecturally hybrid and context-sensitive model of Ukraine's digital recovery.

The entire model is built on causal logic:

DRem → modified through $\psi(t)$ → forms *EffectiveDRem* → influences *RDI*(t).

The structural context of the model is presented in **Fig. 7.6**.

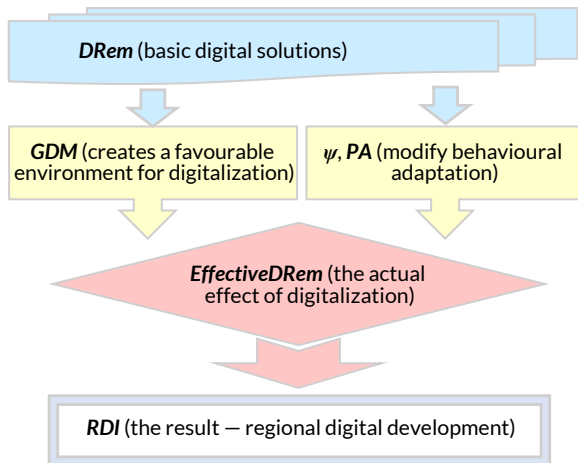


Fig. 7.6 Structural context of the architecturally-hybrid and context-sensitive model of Ukraine's digital recovery

Decomposition of the model architecture can be presented as follows:

Block 0. Regional analysis and diagnostics.

One of the key preliminary elements of the proposed model is the indicator *DNI* (Digital Needs Index) – the index of a region's digital need.

According to the authors' vision, the *DNI* should be included in Block Zero, as it forms:

- the starting point of regional analysis;
- the basis for predictive modeling;
- a filter for the feasibility of implementing digital solutions.

It depends on two parameters:

- ψ (behavioral perception of digitalization) – the readiness of the population and local communities to participate in digital initiatives;
- *RI* (Recovery Index) – the level of restoration of infrastructure, basic safety, housing, and utility systems.

Thus, the formalization of this indicator is as follows

$$DNI_r(t) = (1 - \psi_r(t)) \cdot (1 - RI_r(t)), \quad (7.1)$$

where $\psi_r(t) \in [0.3; 1.0]$ – the coefficient of digital perception of the population in region *r* at time *t* (scientific justification of value limits is provided in Block 2); $RI_r(t) \in [0; 1.0]$ – the recovery index of the region; $DNI_r(t) \in [0; 0.7]$ – the higher the value, the greater the digital need.

A high *DNI* value indicates a digital deficit – that is, a situation in which:

- the population is not ready, but the region objectively requires digitalization due to a low level of recovery;
- or digital initiatives have not yet been deployed, and behavioral inertia remains high.

If *DNI* is low → the need for digitalization is low, and even effective implementation will bring low societal significance. In the authors' opinion, this will help avoid planning errors where digital solutions are implemented and then scaled in conditions where they are either not urgently needed or will not be accepted by the population.

Thus, *DNI* is not a result of digitalization but a function for assessing necessity, applicable at the planning stage.

Block 1. Basic digital technologies (DRem).

These are the basic digital solutions implemented in the region, including the functioning of the Diia platform, the digital cadaster, IoT sensors, etc.

Notation

$DRem_r(t)$,

where r – region; t – point in time.

Block 2. *Modification through perception and condition coefficients.*

The ψ (*psi*) indicator (coefficient of digitalization perception) is a behavioral-contextual variable introduced by us that reflects the population's readiness to use digital solutions. It is not measured directly but can be diagnosed through a set of indicators.

According to the authors, two approaches can be used to diagnose this indicator:

– survey-based or expert assessments (for example, a questionnaire on trust in digital services through the Diia digital platform, or expert assessment of digital literacy based on statistical sampling of user activity data from the Ministry of Digital Transformation of Ukraine);

a) use of proxy indicators, namely:

b) of Diia users – reflects actual use of digital platforms;

c) number of registered users in eRecovery – reflects readiness to participate in digital processes;

d) number of requests for online services – reflects activity and digital need;

e) level of internet coverage and speed – reflects accessibility and inclusiveness of digitalization.

For the purpose of formalizing secondary indicators, the authors introduced the Recovery Index (RI) as a reflection of correlation with the population's basic needs, which directly influences the ψ indicator.

$RI_r(t)$ (Recovery Index) – a normalized indicator of the degree of recovery of region r at time t , calculated within the range from 0 (complete destruction) to 1 (full recovery).

The mathematical formula for its calculation is as follows

$$RI_r(t) = \frac{\omega_1 \cdot I_{infra} + \omega_2 \cdot I_{utilities} + \omega_3 \cdot I_{housing} + \omega_4 \cdot I_{safety}}{\omega_1 + \omega_2 + \omega_3 + \omega_4}. \quad (7.2)$$

Structural components of the index:

– I_{infra} – restoration of critical infrastructure objects (railway stations, bridges, roads, etc.);

– $I_{utilities}$ – availability of access to electricity, water, gas;

– $I_{housing}$ – share of restored residential housing for the population;

– I_{safety} – level of population life safety (including absence of shelling, environmental safety after remediation and demining, etc.).

During the simulation, expert assessments and rating scores on a 0–1 scale were used, as well as open data from the relevant ministries and agencies.

The overall mathematical formalization is represented by the following formula

$$\psi r(t) = \max(0.3, \min(RI_r(t), DI_r(t))) (1 + \lambda \cdot SC(t)). \quad (7.3)$$

The interpretation of the indicator is as follows:

- $RI_r(t)$ – defines the physical and social readiness for digitalization;
- $DI_r(t)$ – Digital Inclusion Index defines technological and behavioral inclusiveness;
- C (*Social Capital*) a modifier of ψ reflects the level of trust and participation,

where λ is the weight of trust;

– ψ – represents the final behavioral coefficient of digital perception with a lower limit of 0.3 (apathy, rejection), above which digitalization begins to be "perceived".

It is possible to model $\psi \in [0.3; 1.0]$, where:

- 1.0 – full readiness (maximum perception);
- 0.3 – threshold of apathy or social rejection, below which digitalization loses

its meaning.

The authors of the monograph rely on the interpretation of the five-point Likert scale, which is widely used in empirical social and behavioral studies (Table 7.3) [15].

Table 7.3 Application of the Likert scale in behavioral research

Evaluation	Behavioral interpretation
1.0	Fully agree/active acceptance
0.75	Rather agree/positive receptiveness
0.5	Neutral/cognitive inertia
0.3	Rather disagree/apathy, rejection
<0.3	Complete refusal to participate/destructive perception

Thus, the practical significance of the obtained results will be interpreted as follows:

– if $|\psi < 0.3| \rightarrow$ then digitalization is not perceived, and behavioral interventions must be implemented;

– if $|\psi = 0.3| \rightarrow$ then social inertia is observed, and there is a minimal digital basis;

– if $|\psi > 0.5| \rightarrow$ then digitalization begins to produce an effect in the Effective DRem model;

– if $|\psi \rightarrow 1.0| \rightarrow$ then full digital maturity is observed, which indicates ideal conditions [16–18].

Block 3. GDM (Governmental Digital Mobilization) – index of governmental digital mobilization.

GDM is an aggregated indicator of the level of institutional activity, political will, and systemic support for digital transformation by government authorities at the national, regional, and local levels. It reflects the intensity and quality of the state's participation in creating conditions for the digitalization of regional development, especially in the context of post-war remediation, housing and infrastructure recovery, social and medical services, as well as transport provision and communication with the population [4, 7].

It should be noted that, according to the scientific views of Douglass North and other representatives of the new institutional school, the quality of institutions and the effectiveness of their actions directly determine the success of any transformational processes, including technological and digital ones. The aggregated GDM indicator can reflect: the density of digital institutions (including Diia, Prozorro, etc.); the volume of funding for digital development; the level of decentralization and digital autonomy of regions [18].

According to the authors' conviction, even with a high level of digital solutions ($DRem$) and population perception (ψ), the absence of institutional support leads to: lack of coordination in digital processes; data fragmentation; slowdown of the RDI (Regional Development Index). GDM can be included in the formula for calculating the optimal level of digitalization

$$EffectiveDRem_r(t) = DRem_r(t) \cdot \psi_r(t) \cdot PA_r(t) \cdot (1 + \mu \cdot GDM_r(t)), \quad (7.4)$$

where μ – the weighting coefficient of amplification from institutional mobilization.

Block 4. PA – Phenotypic adaptation, which means the extent to which digital solutions are adapted to local conditions (actual destruction, staffing, internet availability, living conditions of the population, etc.).

As described earlier, phenotypic adaptation represents a bio-inspired methodological principle borrowed from biology, in which the behavior, functions, and properties of a system (in this case – a digital platform or architecture) are modified depending on environmental conditions, while preserving its general "genotype", that is, the basic architecture of digitalization.

Within the studied model, the key elements of PA are:

- the "genotype" is the core of the digital platform (including, for example, Diia, eRecovery, etc.);
- the "phenotype" is the specific way it is implemented, including the interface, digital accessibility, methods and channels of scaling, as well as the adaptation of the platform taking into account regional differences and needs.

As described in the previous block, PA is included in the calculation of effective digital remediation as a modifying adaptive coefficient.

$PA_i(t) \in [0.5; 1.0]$ is capable of reflecting the degree of adaptability of a digital solution to the conditions of a specific region. Values below 0.5, according to the authors of the study, will be destructive – when a centralized solution "breaks" against local reality (technically, legally, behaviorally).

Why is this critically important in the context of Ukraine? The fact is that since the beginning of active military actions in February 2022, Ukraine has become a country with extreme regional asymmetry, namely:

- some regions are radically destroyed and continue to suffer the consequences of military activities (Mariupol, Kharkiv, Kherson, etc.);
- others are partially affected and have partial consequences from military actions (Kyiv, Chernihiv, Zhytomyr, Vinnytsia, etc.);
- a third group of regions is comparatively stable (Lviv, Ternopil, Ivano-Frankivsk, etc.).

According to the authors' conviction, implementing the same approach to smart economy development across all regions (following the logic of "Smart Nation") may lead to misunderstanding, cognitive rejection, and overall technical infeasibility of use.

In contrast to this, PA proposes the model of "Smart Regions" – dispersed adaptation of digital solutions taking into account phenotypic differences.

7.4 Current assessment and prospects for the implementation of smart economy principles at the regional level: model testing and validation

The model developed within the framework of this monographic study represents an architecturally hybrid digital system, built on causal relationships between the implementation of digital solutions ($DRem$), behavioral perception of the population (ψ), solution adaptability (PA), digital need (DNI), institutional support (GDM), and the final result in the form of the Regional Digital Development Index (RDI).

In order to confirm the realism, applicability, and predictive accuracy of the proposed model under Ukrainian conditions, it is necessary to carry out two stages:

Stage I. Model testing (approbation).

Stage II. Model validation.

Thus, approbation is the process of experimental application of the model on a limited set of empirical data or regional cases, in order to:

- test the adequacy of the proposed hypotheses and the logic of interrelations between the indicators described above;

- identify behavioral, institutional, and technical features of regional development;
- detect bottlenecks and risks related to the transition of the model from theoretical to applied use;
- assess the sensitivity of the developed model to changes in key parameters.

As part of the approbation process, it was decided to test the model on three typologically different regions of Ukraine, reflecting the full spectrum of regional asymmetry characteristics. In turn, validation is the scientific verification of the model's correctness, which focuses on:

- comparing the obtained modeling results with actual or close-to-reality scenarios;
- assessing the consistency of the model's internal relationships with the logic of real post-war regional recovery and development processes;
- measuring the accuracy, sensitivity, and resilience of the model to various input data;
- identifying discrepancies and refining the model's parameters (including indicators such as ψ , GDM , PA , SC , DNI).

Validation will be based on statistical, expert, and scenario analysis methods (including correlation analysis, scenario modeling with fluctuations, as well as comparative analysis of logistic growth charts).

As part of the testing and validation of the digital recovery model of Ukraine based on smart economy principles, an integration of several types of tools, software, and computational resources, scientifically grounded, was used.

Table 7.4 presents a detailed description and structured explanation.

Table 7.4 Tools and software used for model testing and validation

Tool/Environment	Purpose	Characteristic
Python (v3.11)	Algorithmic implementation of the model	Open scientific environment, supports large-scale simulations
NumPy, Pandas	Data formalization and storage, statistics	Processing of time series and matrix structures
Matplotlib, Seaborn	Visualization of growth dynamics and region comparison	Graphs of $RDI(t)$, $\psi(t)$, $EffectiveDRem(t)$
Jupyter Notebook	Documentation of simulation and scenarios	Enhances transparency and reproducibility
QGIS	Spatial validation and mapping of regional differences	Visualization of ψ , RI , DNI levels across regions
SPSS/Excel	Post-processing and statistical verification	Calculation of averages, deviations, correlations

The next step of the study is the cluster selection of regions – based on the criterion of the degree of destruction and the impact of the war (Table 7.5). According to the authors of the study, this creates ideal conditions for comparative verification simulation. All of this will allow for testing the validity of the selection of key indicators in the mathematical model, validating the model as a whole, and most importantly, confirming the applicability of the theoretical and methodological approaches of the regional digital development strategy.

Table 7.5 Proposed regions for cluster modeling: characteristics and justification

Cluster	Region	Characteristic	Reasons for Selection
1. Catastrophic level of destruction	Kherson	Massive destruction, daily military actions, destruction of Kakhovka HPP, environmental catastrophe, mass migration	Maximum load on the digital remediation system
2. Medium level of destruction	Chernihiv	Significant destruction in 2022, but partially restored, presence of civil administration	Medium level of adaptation, cases of local digitalization
3. Almost no destruction	Ternopil	No hostilities, calm situation, internal migration, high digital engagement	Reference region – condition of a "normal" smart economy

As previously noted, Ukraine is currently facing high asymmetry, namely:

- in the nature and scale of destruction (different *RIs*);
- in the level of digital maturity;
- in the population structure (internally displaced persons, socially vulnerable groups, working-age population);
- in access to basic services.

At the same time, the same digital platform may be in demand in Ternopil region (high digital need), yet ignored in Kherson region (where the population has not yet restored its basic life functions). This means that the implementation of digital policy must rely not only on ψ and *DRem*, but also on the digital need parameter.

According to the authors, this forms the fundamental core of the digital transformation model in the context of post-war recovery – the interconnection between digital need, digital remediation, and the smart economy of the regions.

The next step was to carry out simulation modeling of ψ and *DNI* across the selected sample of regions (Table 7.6).

To obtain the results of the simulation modeling, a parametric model was used, implemented in the MS Excel environment with the use of built-in logical-arithmetic formulas and customizable simulation tables, as well as software tools Statistica and

Python (NumPy and Pandas libraries) for the verification of calculations and scenario construction. The modeling was carried out using the method of deterministic simulation, based on predefined input coefficients (ψ , RI , GDM , PA) and multiplicative relationships between them.

Table 7.6 Digital perception and needs diagnostics table

Region	Digital Usage	Internet Coverage	Infrastructure Access	Recovery Index (RI)	Digital Perception (ψ)	Digital Need Index (DNI)	GDM	PA
Kherson Region	0.21	0.31	0.28	0.23	0.32	0.52	0.42	0.50
Chernihiv Region	0.49	0.76	0.62	0.72	0.62	0.106	0.61	0.65
Ternopil Region	0.86	0.92	0.89	0.93	0.91	0.006	0.87	0.93

The obtained results confirm the identification of clearly expressed regional differentiation and the logical choice of the Kherson, Chernihiv, and Ternopil regions as representative polar case studies in the context of post-war digital recovery. Thus, the Ternopil region demonstrates a mature digital environment with a high degree of perception and adaptation ($\psi = 0.91$; $PA = 0.93$) and minimal digital need ($DNI = 0.006$), which indicates a high institutional and social readiness for the implementation of comprehensive digital solutions.

At the same time, the Kherson region stands out as the region with the highest digital need ($DNI = 0.52$) among all regions in the sample, against the background of the lowest level of digital perception ($\psi = 0.32$), which indicates weak adaptation and a low level of institutional support. This makes the region a clear example of inertial digital development, requiring prioritization of efforts in the direction of technological and managerial impact in the context of remediation and post-war socio-economic recovery. The Chernihiv region occupies an intermediate position, characterized by a moderate level of perception ($\psi = 0.62$) and a relatively low digital need ($DNI = 0.106$), reflecting the transition phase toward a smart regional model, where the factors of adaptability, trust in digital services, and the ability of government structures to ensure the inclusiveness of digital solutions play a special role. *This allows to conclude that Ternopil Region is a region where digitalization works, and the population is actively engaged in the smart economy.*

The next step was the construction of scenario development graphs showing the S-shaped growth of RDI depending on ψ . (Fig. 7.7).

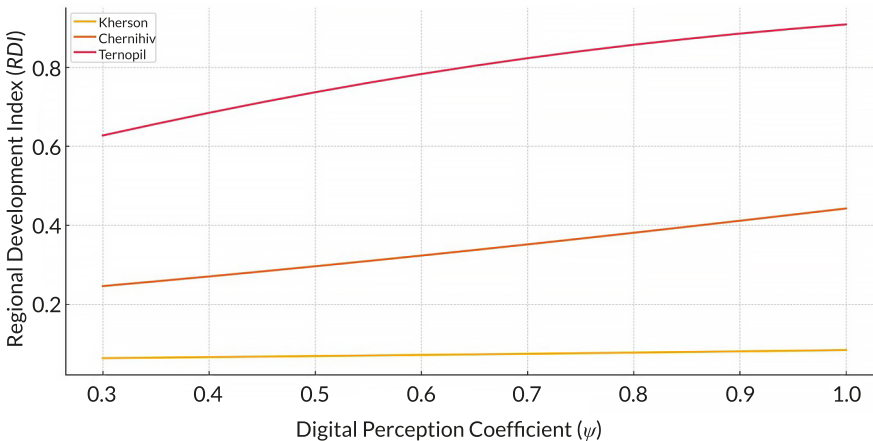


Fig. 7.7 Logistic growth: RDI and digital perception (ψ) in the context of Kherson, Chernihiv, and Ternopil regions

The presented graph reflects the following:

- In Kherson region, the growth of *RDI* begins only after surpassing the threshold of $\psi \approx 0.4$ – 0.5 . Before this, almost zero sensitivity is observed;
- Chernihiv region enters the "active phase" of digital growth more quickly, but also requires time to accelerate;
- Ternopil region, unlike the other two regions in the sample, is initially at a high level, so growth begins earlier and reaches saturation already at $\psi \approx 0.7$ – 0.8 .

Next, a simulation of digital dynamics over the time period 2025–2032 was conducted for the three regions. The authors of the study set the following objectives:

- to forecast when each region will enter the "active phase" of digital growth;
- to identify the transition point (ψ_0) after which digitalization begins to significantly influence regional development;
- to assess the pace, barriers, and potential of the growth scenarios for ψ , *DNI*, *PA*, and their contribution to the formation of *RDI* (regional growth) over time (**Fig. 7.8**).

The simulation results allow the interpretation as follows:

- in Kherson region, slow growth of *RDI* is observed until 2028–2029, followed by a noticeable acceleration. This corresponds to the "entry into the active phase of digital growth" after surpassing the critical $\psi \approx 0.54$;
- in Chernihiv region, the beginning of the active phase of digitalization is forecasted around 2026. At the same time, a moderate growth trajectory is

observed, without saturation – by 2032, the potential for digitalization development still remains;

– in Ternopil region, digital active development is currently taking place, but saturation is forecasted closer to 2029. This is one of the examples of regional development where early digitalization quickly transitions into a stage of maturity.

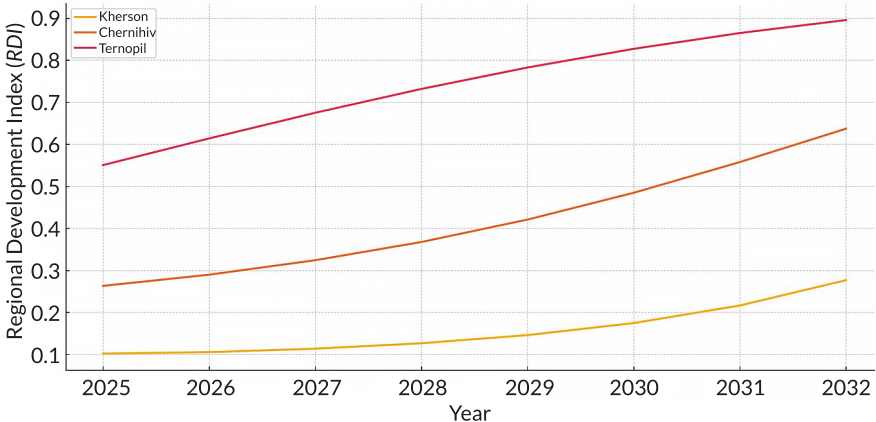


Fig. 7.8 Forecasted effective digital remediation of key parameters across Kherson, Chernihiv, and Ternopil regions for the years 2025–2032

The next logical step will be the study of complex dynamics across five key parameters for each region for the period 2025–2032 (**Fig. 7.9**).

At the conclusion of the analytical part of the study, a correlation analysis was conducted and the sensitivity of the model was evaluated (**Table 7.7**).

Based on the calculated data, the following conclusions and generalizations can be made. The conducted study confirmed the necessity of a differentiated approach to implementing digital strategies depending on the specific conditions of each region:

- in regions with a high degree of destruction (such as Kherson region, etc.), digital initiatives have a limited effect unless accompanied by the restoration of basic infrastructure and growth in public trust;
- in regions with medium destruction (such as Chernihiv region, etc.), digital initiatives are positively perceived and ensure stable growth;
- in regions without significant destruction (such as Ternopil region, etc.), a saturation effect of digitalization is observed, requiring a focus on innovative approaches rather than on the quantitative expansion of digital initiatives.

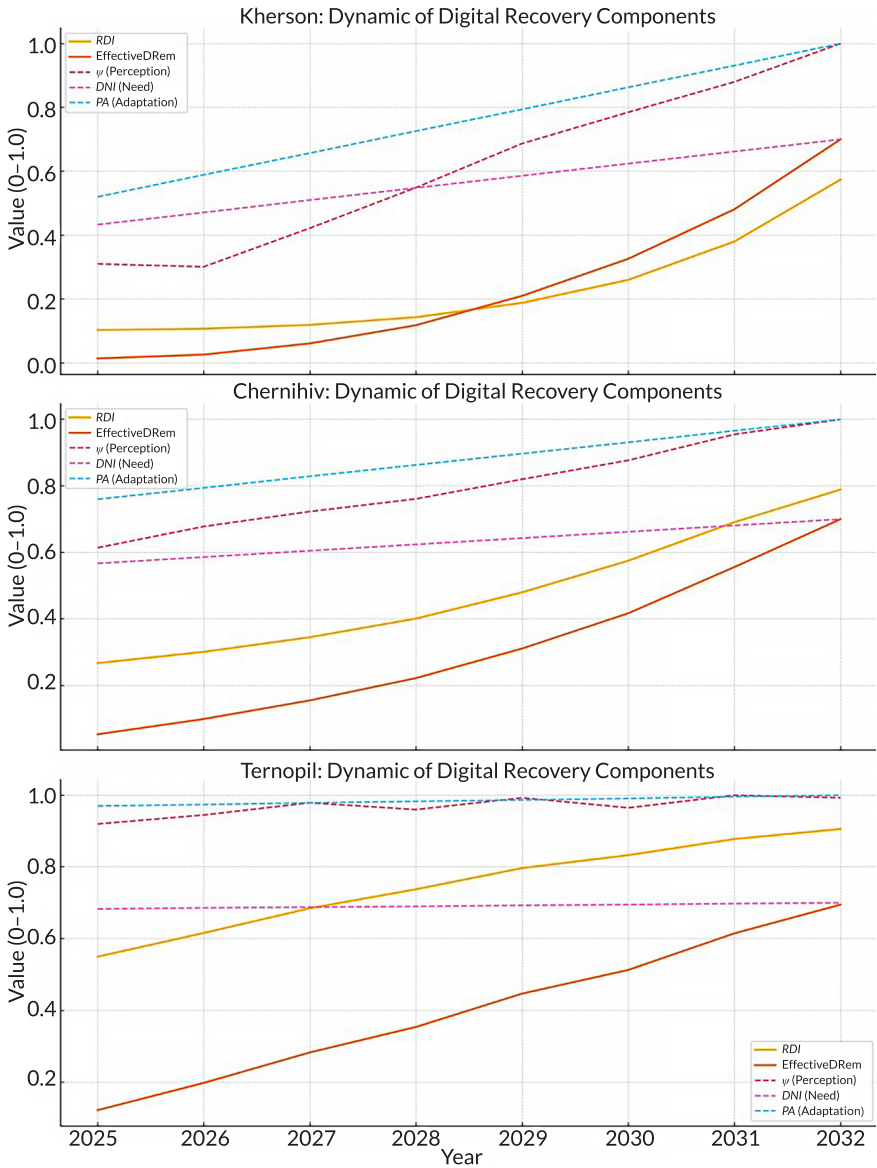


Fig. 7.9 Comprehensive dynamics of key parameters across Kherson, Chernihiv, and Ternopil regions for the years 2025–2032

Table 7.7 Results of correlation and sensitivity analysis of the model

Region	Correlation (r)	$\Delta RDI/\Delta DRem$	R^2	Description of results
Kherson Region	0.851	0.723	2.401	Strong correlation; digitalization "works" only with the growth of ψ
Chernihiv Region	0.947	0.896	1.036	Almost linear dependence, even considering behavior; well perceived
Ternopil Region	0.651	0.424	0.482	Saturation effect appears – digitalization is perceived steadily, but RDI growth slows down

The correlation analysis demonstrates the fact that the hypothesis about the non-universality of the digitalization effect under different recovery conditions is confirmed. Moreover, under the same digitalization principles, the regions produced different digital development trajectories. All of this confirms the idea of an adaptive model sensitive to local conditions. In the context of state governance of regional development, this means that a unified template for digital remediation and recovery cannot be applied to all regions. According to the authors' view, the most reasonable course of action would be:

- to assess the region's sensitivity to digitalization;
- to forecast the saturation effect;
- to launch pilot projects based on the principle of emergent ecosystems, rather than directive reforms.

Within the constructed model, dynamic simulation of key components of digital recovery was carried out for three regions with different levels of destruction and institutional capacity: Kherson, Chernihiv, and Ternopil regions.

Kherson region – "Delayed Start" scenario. The model demonstrates extremely slow development of the Regional Development Index (RDI) in the first years of simulation forecasting. Despite the growth of the formal level of digital remediation ($DRem$), the key parameters – the digital perception coefficient (ψ), the Digital Needs Index (DNI), and the phenotypic adaptation coefficient (PA) – remain at a low level up to 2028. This confirms a high level of behavioral inertia, distrust, and the prioritization of basic needs over digital initiatives under conditions of prolonged military threats and destruction. The activation point of digital growth (in terms of RDI) is forecasted for 2028. The management conclusion drawn by the authors is that the most appropriate actions would be the implementation of soft forms of public engagement, building trust in digital platforms, their scaling, and simultaneous deployment of locally adaptive services.

Chernihiv region – "Balanced Growth" scenario. The model shows steady growth of ψ and *EffectiveDRem* from the current period, i.e., from 2025, which is reflected in the progressive growth of *RDI* starting in 2026. According to the forecast, the region enters the active phase of digital recovery under conditions of a moderate level of destruction (as recorded during the simulation), already formed experience of digital interaction, and institutional flexibility. The activation point of digital growth is forecasted for 2026. The management conclusion of the monograph's authors is that the region is ready for the scaling of digital practices, including through the integration of local and national platforms, and the optimization of interaction between authorities and the population via digital services.

Ternopil region – "Early Saturation" scenario. The simulation results show that the region possesses high initial digital receptiveness. Already in 2026, an entry into the active growth phase of *RDI* is observed, however by 2029, a slowdown in growth rates is expected due to reaching the upper limits of *EffectiveDRem* and institutional base saturation. This is a typical case of the digital plateau effect, when formal digitalization growth ceases to significantly influence socio-economic indicators. The activation point of digital growth is forecasted for 2026. The management conclusion to be drawn is that in regions like Ternopil, it is advisable to transition from implementing digital solutions to qualitative modernization, ensuring cyber-resilience, and digitally scaling into adjacent territories.

7.5 Regional stratification as a tool for context-sensitive management of digital transformation in the conditions of Ukraine's post-war recovery

By regional stratification, let's mean the process of systematic classification of regions based on their degree of digital receptiveness and actual readiness for digital transformation, using the key indicators of the model proposed in the study, namely: ψ (coefficient of digital perception of the population); *RDI* (integral index of regional digital development). Stratification in this context is based on the results of simulation modeling, where each region was assessed by the growth trajectories of *EffectiveDRem* and the logistic function *RDI(t)*.

According to the authors' conviction, regional stratification is a critically important tool for transformational governance under post-war recovery conditions. It allows the architectural flexibility of the model to be combined with institutional realism and socio-behavioral sensitivity, thereby providing a foundation for a fair and effective digitalization of Ukraine [19].

In our view, regional stratification can ensure built-in adaptability of the entire architecture of the proposed digital recovery model. It reinforces the principles and reveals the theoretical-methodological foundation on which it is built, namely:

- phenotypic adaptation – each region receives its own digital phenotype;
- inclusiveness of digitalization – stratification reduces the risk of digital inequality;
- digital cohesion, which means that regions with different levels of maturity are connected to a shared digital infrastructure, but with different depth and speed;
- emergent strategy – decisions are formed based on the analysis of regional cases and are not imposed from above [20].

Regional stratification allows for the implementation of four interrelated functions:

- differentiated governance – the ability to form strategies not on the principle of "one format for all regions" but on demand;
- resource optimization – a rational approach to providing resources for digital transformation, meaning resources are directed where the effect will be maximal;
- justification of the prioritization of digital remediation in the context of identifying territories with the greatest need and impact potential;
- creation of a digitalization roadmap – stratification can form the foundation for the phased digital activation of regions by identifying growth points [21].

The simulation showed that: in Ternopil region, the $RDI(t)$ growth curve has a steep logistic character, confirming readiness for digitalization scaling; Chernihiv region demonstrated moderate dynamics and correlation with targeted digital interventions; Kherson region showed $\psi = 0.32$, which, according to the model, indicates a lack of behavioral readiness for digital remediation. This result highlights the need to implement basic infrastructural and trust-building measures, as well as significant state support in this regard.

Thus, the developed model and regional stratification have practical significance and can be used by government authorities to form region-oriented strategies for digital transformation. It enables forecasting and evaluating the effectiveness of digital solutions in the context of post-war remediation, as well as determining the priority of regional investments and digital interventions.

7.6 Conclusion

In the presented study, theoretical notions of digital remediation as an instrument of regional recovery policy are expanded. An interdisciplinary foundation is created for assessing the digital receptiveness of regions based on models that combine behavioral economics, the theory of sustainable development, and information technologies [22].

Overall, the conclusions and generalizations made by the authors indicate that digital technologies and solutions can and must become the core of Ukraine's post-war development strategy. The principles of the smart economy – innovation, data orientation, openness, and flexibility – have already proven effective in local situations during the war. The current task is to scale them up across the entire country during the post-war recovery period. Of course, this implementation will require coordinated efforts from all stakeholders: the government, business, the scientific community, international partners, and the citizens themselves. But the potential benefits are immense – from accelerating GDP growth to transforming Ukraine into a competitive player in the global digital economy [22, 23].

The architecturally hybrid and context-sensitive model of digital remediation of Ukraine, developed and presented in the monograph, offers a scientifically grounded basis for the implementation of differentiated regional development strategies, based on adaptability, inclusiveness, and scalability of digital transformation. Regional stratification, as a key mechanism of this model, will enable decision-making that aligns digital policy with local needs, capabilities, and the population's behavioral readiness. The implementation of the model proposed by the authors will contribute to strengthening strategic coherence between national objectives and regional development trajectories, transforming digitalization from a fragmented process into a catalyst for progressive and sustainable post-war revival of Ukraine [24, 25].

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